Phase 1 Validation Test Report:
Offline Testing of the CUB 1.0 Model

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Summary

This report documents the results of a series of offline relocation tests conducted for model validation and to test simulated location improvement in the IMS network should the CUB 1.0 Model SSSCs be installed.

A benchmark test relocating GT0-25 reference events previously used to test Fennoscandian 1D SSSCs was conducted. The objective of this test was to establish significant operational differences would exist between new 3D SSSCs and old 1D SSSCs for Fennoscandia. No such significant differences could be found. The results of these tests indicate that there should be no impact in replacing the existing 1D SSSCs with 3D SSSCs in Fennoscandia. The new 3D SSSCs perform as well or better than the existing 1D SSSCs in Fennoscndia. Replacement of old 1D SSSCs in Fennoscandia with a consistent set of 3D SSSCs for all of Europe would do no harm.

Model validation tests were conducted relocating 571 GT0-10 events from the Group 2 Location Calibration Reference Event List 1.1. The CUB 1.0 Model based SSSCs and model errors performed well w.r.t. IASPEI91. More events were better located. Fewer events were worse located. More events were located closer to GT. Origin times were closer to GT. General misfit was reduced. Degradation is less than expected from the error model and test data set. Model errors predicted “honest” 90% error ellipses. Model errors may be over conservative for 50% of events but under estimated for 5% of events. IASPEI91 travel time tables performed better than should be expected given the current IDC model errors.

Relocation tests using the Mid-Ocean Ridge and Transform (MORT) GT10 events reveal the strong sensitivity of location algorithms to outliers in the distance range of 15 to 20 degrees due to misassociation of P to Pn. Given the limited number of 15 MORT events that could be located with arrivals within 15 degrees, the test shows only marginal improvement in locations consistent with a “do no harm” conclusion. The percentage of events that failed the 90% coverage test is only slightly below what could be expected based on the sample size.

Relocation tests of 435 candidate GT5 events from the EHB bulletin were conducted for model validation. The test results show the 3D SSSCs "do no harm" to locations. This data set has poor resolving power to demonstrate improvement. While the model error under predicts at the 90th percentile error, it correctly predicts the 50th percentile coverage.

A total of 240 and 318 reference events were relocated using only IMS stations and IMS plus IMS surrogate stations to simulate regional location with calibrated Pn and Sn phases in an IMS network. These test results demonstrate SSSCs should improve locations based on regional data for a fuller IMS network. Calibration does more improvement and causes less harm than no-calibration.

Tests were repeated with calibrated Pn and Sn phases combined with uncalibrated Pn and Sn phases in a simulated IMS network. The results of this test indicate that mixing calibrated and uncalibrated regional phases in the IMS network does not do significant harm. The improvements in calibration are only generally diluted.

Tests were repeated with calibrated Pn and Sn phases combined with uncalibrated Pg and Lg phases in a simulated IMS network. The results of this test show that, although it is undesirable to mixed calibrated with uncalibrated regionals for the same stations, the mixing “does no harm” to event location in such a situation.

Tests were repeated with calibrated Pn and Sn phases combined with uncalibrated teleseismic phases in a simulated IMS network. The results indicate event location is improved by Pn and Sn SSSCs for simulated IMS networks even with large numbers of teleseismic phases.

Tests were repeated with calibrated Pn and Sn phases combined with uncalibrated Pg, Lg, and teleseismic phases in a simulated IMS network. The test results show that the Pn and Sn SSSCs at least “do no harm” in event location when mixed with uncalibrated regional and teleseismic phase in a simulated IMS network. However, the test results from the full set of events did not simulate the situation of a small event detected by the IMS network.

Tests were repeated with a subset of events with fractions of regional to teleseismic phases that more represent small events detected in an IMS network were selected. This simulation argues that Pn and Sn SSSCs will improve locations for small events in the IMS network when mixed with uncalibrated regional and teleseismic phases.

1.0 Introduction

This report summarizes offline validation test results of SSSCs from the CUB 1.0 Model, as outlined in our Phase 1 Validation Test Plan (Group-2 Location Calibration Consortium, 2001). We discuss validation testing, evaluation metrics, test data sets, and test results of the Pn and Sn SSSC offline testing using the location program EvLoc. These tests are conducted to validate the CUB 1.0 Model and expected IMS location improvement. Validation testing for the SAIC-HRV model is summarized in a separate report (Yang et al. 2001). Online testing for the Automatic (Global Association, GA) and Interactive (Analyst Review Station, ARS) Systems has been successfully conducted on the DTRA CMR R&D Testbed (Oancea and Caron, 2001).

The successful development of Source Specific Station Corrections (SSSCs) for Fennoscandian and North American IMS seismic stations demonstrated that event locations and uncertainties can be improved by applying regional travel time corrections for event location (Yang and McLaughlin, 1999, 2000). The approach was to develop model-based travel-time corrections and then use Ground Truth (GT) data for validation. At present, regional SSSCs are applied for seismic event location to calibrate the default IASPEI91 travel times used at the PIDC/IDC for both Fennoscandia and North America.

The Group-2 Consortium carries out seismic location calibration for IMS stations in the Mediterranean, North Africa, Middle East, and Western Asia using 3D seismic velocity models. SSSCs for IMS seismic stations in the region are developed to improve location accuracy and reduce error ellipses. Our goal is to develop SSSCs for Pn, Sn, and Lg out to 20 degrees and Pg out to 8 degrees for all primary and auxiliary IMS stations in the study region (Figure 1). The work consists of two phases. In the first phase we developed preliminary Pn and Sn SSSCs for sources at 10 km depth. In Phase 2 we will refine and improve the models and methods to obtain final corrections, including depth dependence. Pg and Lg SSSCs will also be developed in Phase 2. In both phases, validation testing is conducted using GT events to demonstrate improvement of event location. This report describes validation testing results of Phase 1 Pn and Sn SSSCs that have been delivered to and tested by the DTRA CMR R&D Testbed.

The 3D model (CUB 1.0 Model) was constructed by combining global mantle models with global crust and upper mantle models using improved group and phase velocity data sets and inversion methodology (Shapiro and Ritzwoller, 2001). SSSCs are calculated for a given station using ray tracing. The Group 2 Consortium has collected GT reference events and candidate reference events for model validation and IMS location improvement demonstration. Validation testing of the model-based SSSCs is conducted by relocating GT0-GT10 events. Phase arrivals from IMS stations and IMS surrogate stations as well as any other available stations are used. We evaluate reductions in mislocation and error ellipse area and coverage. Results discussed in this report are for Pn and Sn SSSCs from the CUB 1.0 Model only.

SSSCs are defined on a rectangular latitude/longitude grid where both a travel-time correction and a modeling error are assigned to each grid point. The corrections are given relative to the default IASPEI91 travel time tables. Grid spacing was chosen as one degree for both latitude and longitude. In Phase 1, regional SSSCs are computed for Pn and Sn phases out to 20 degrees for IMS stations, surrogate/other stations, and any other stations in the study region required for the tests.

The Phase 1 modeling errors (Figure 2) were obtained from travel time misfit of the CUB 1.0 Model with respect to for arrivals in the EHB catalog (Engdahl et al., 1998). A simple distance dependent, azimuthally independent, station independent model error was selected for Phase 1 (Bhattacharyya et al., 2001).

In addition to the relocation testing described in this report, validation testing is also being carried out using other methods, e.g. cluster analyses (Engdahl and Bergman, 2001; Israelsson et al., 2001). The Joint Hypocenter Determination (JHD) and Hypocenter Decomposition (HDC) cluster analyses are used to derive path-dependent corrections from event clusters, recorded by IMS stations, their surrogates and other teleseismic/regional stations. Comparison are made between these empirical corrections and model-based SSSCs for cross validation (Figure 2). Station corrections and statistical scatter of clusters are used as one source of information in estimating modeling errors.

The scope of this report is to document validation test results from GT event relocations using CUB model SSSCs. This report does not describe the 3D models, the raytracing, the errors models, or the reference event data collection, which are given in other Phase 1 delivery documentation.

2.0 Validation testing and evaluation metrics

Validation testing of regional SSSCs in the Group-2 Consortium region of interest is conducted by relocating events using SSSCs to verify event location improvement relative to GT location and error ellipse size and coverage. Events used in validation testing are mainly GT0-GT10 events (Section 3) and were not directly used in model development. Validation offline tests include model validation tests and IMS location improvement tests. Each test is conducted by relocating events using the location program EvLoc. EvLoc utilizes the same library, libloc, used by the IDC in automatic and interactive processing. Evaluation metrics are developed to measure improvement/degradation in location, location uncertainties and coverage when corrections are applied, with respect to the default travel time tables. We assess statistics on mislocation, error ellipse area, 90% error ellipse coverage, origin time difference from GT, origin time error, and standard deviation of observations.

For model validation, SSSCs for as large a set of stations as possible are applied to validate/test the 3D models and model errors in the study region (Figure 3). When SSSCs are applied, event location should be improved for the majority of events, improvement should be greater than deterioration, and error ellipses should be significantly reduced without loss of 90% coverage.

For the IMS network validation test, the objective is to demonstrate location improvement in the study region using regional SSSCs for IMS stations and IMS surrogate stations (Figure 4). IMS surrogate stations are used to simulate the IMS network where future IMS stations are not yet deployed and/or data are not available from existing IMS stations. Surrogates are limited to stations within 75 km of the corresponding IMS stations. Unlike the model validation test, this test applies only to IMS stations and their surrogates for regional phases. The effect of mixing calibrated regional arrivals with uncalibrated regional and teleseismic data is evaluated. Four sets of network configurations are tested by locating events only using IMS/surrogate stations:

- Calibrated regionals only: locations with and without Pn and Sn SSSCs, with no other defining phases. This test validates the regional travel time model by separating the effect of calibrated regional SSSCs from the contributions of teleseismic phases and other uncalibrated regional phases in event location.
- Calibrated and uncalibrated regionals: location with and without Pn and Sn SSSCs, including uncalibrated Pn, Sn, Pg and Lg defining phases. This test evaluates the effect of mixing calibrated and uncalibrated regional phases.
- Calibrated regionals and uncalibrated teleseismics: location with and without Pn and Sn SSSCs combined with teleseismic defining phases. This test evaluates the effect of mixing calibrated regional phases and uncalibrated teleseismic phases.
- Calibrated regionals, uncalibrated regionals, and teleseismics: location with and without Pn and Sn SSSCs combined with all other defining phases. This test demonstrates compatibility of calibrated Pn and Sn phases with uncalibrated Pg, Lg phases, and uncalibrated teleseismic phases. This simulates the way in which Phase 1 SSSCs would be implemented in the IDC/ PIDC operations.

Our principal evaluation metrics include recommendations by the 1999 Oslo Location Workshop (CTBT/WGB/TL-2/18, 1999):

- The median mislocation of GT events should be significantly reduced.
- Mislocation should be reduced by 20% or more for a significant number of the events.
- Median area of error ellipses should be reduced, and the coverage (percentage of GT events lying within the error ellipse) should be similar.
- Error ellipses should be reduced by 20% or more for the majority of the events.
- Fit, as expressed by residuals or their variance, should be similar or better.

Additional metrics were developed to measure the performance of the SSSCs as detailed in Appendix 1. Both L1 norm (median, spread, min, max, percentiles) and L2 norm (mean, variance, standard deviation, average deviation) statistics were calculated for distance from GT, size of error ellipse, ellipse coverage, origin time, origin time error, and misfit (standard deviation of observations, sdobs) with and without calibrations. Student-T and Wilcoxon significance tests of paired samples are applied. In the following Sections we generally give significant test results at the 95% confidence level.

Besides applying the above evaluation metrics, we further evaluate the details of event mislocation. We divide the relocated events into several classes based on the GT accuracy, i.e. within vs. beyond GT accuracy when located with and without corrections. Class C0 is used for GT0 events. Similarly, we divide the data into several classes based on mislocation, i.e. within vs. beyond 18 km when located with and without corrections. The definition of these two classes are given in the table below. Classes C1 and D1 are measures of "do no harm" in validation testing, since these events are well located (within GT tolerance and 18 km, respectively) regardless of calibration. Classes C2 and D2 measure location improvement with SSSCs while Classes C3 and D3 measure deterioration. We use these class notations in the following Sections.

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with SSSCs	without SSSCs	
	within GT accuracy	**beyond GT accuracy**
within GT accuracy	Class C1	Class C2
beyond GT accuracy	Class C3	Class C4
	within 18 km	**beyond 18 km**
within 18 km	Class D1	Class D2
beyond 18 km	Class D3	Class D4

We count the number of events (with and without calibration) in a data set which are 1) located with an error ellipse smaller than 1000 km^2, 2) the error ellipse contains GT, and 3) the mislocation is less than 25 km. This statistic is designated TRINITY in the following Sections. It provides some qualitative indications of how calibration moves toward the CTBT performance goals. However, since most of the reference events are located using only subsets of available arrivals and stations, we should expect the event locations to be generally poorer than can be achieved when all data are utilized. Our goal is to directly compare the location results with and without SSSCs. Regardless of the final locations, calibrations are successful as long as the relative location parameters are improved with SSSCs.

In addition to the tests using GT0-GT10 events, it is also important to test regional SSSCs using as large a data set as possible to identify possible problem areas. This last series of tests are largely a "do no harm" tests, and events in these data sets may be GT10. These tests differ from the testing using GT events in that the events may lack sufficient accuracy for strict statistical tests to have enough power to make a definitive pass/fail criteria. While the location improvement using SSSCs may be ambiguous due to the uncertainties in the locations of the candidate events, the SSSC performance serves as a bottom line check in which SSSCs should not degrade routine event location performance.

3.0 Test data sets

Four data sets of events and associated arrivals were used:

- The first data set includes over 600 GT0-25 reference events used in previous 1D SSSC tests for Fennoscandia (Yang and McLaughlin, 1999).
- The second data set includes over 600 GT0-GT10 reference events from the Group-2 Location Calibration Consortium Reference Event List 1.1 database (Bondár et al., 2001).
- The third data set includes 35 GT10 Mid-Ocean Ridge and Transform (MORT) events (Antolik, 2001).
- The fourth data set includes over 400 “candidate” GT5 events from the EHB bulletin (Gupta and Wagner, 2001).

Since the expected improvements in location are on the order of 10 km, the location accuracy of reference events should preferably be 5 km or better. Therefore, we mainly focus on GT0-GT5 events for relocation and error ellipse validation, but other events are also used for validation testing to extend path coverage in the region.

3.1 Fennoscandia Data Set

The Fennoscandia data set was used to test 1D SSSCs for Fennoscandian stations in 1999 (Yang and McLaughlin, 1999). It consists of three subsets of data, the GTX data subset, the CEB (CMR Calibration Event Bulletin; now Reference Event Database) data subset, and the NZ (Novaya Zemlya) data subset. The GTX data subset includes 425 events that can be relocated using only regional phases. The events were considered as GT0-GT2 events at that time. 181 of these events have been included in the Group-2 Consortium Reference Event Database. 50 events are now classified as GT5 instead of GT0-GT2. The CEB data subset includes 43 CEB events, mostly along the North Atlantic ridge. The NZ data subset includes 5 events in Novaya Zemlya/Kara Sea with JHD locations. Figure 5 shows events in this data set.

The objective of using these benchmark data sets is to compare a self consistent set of SSSCs from 3D models within 20 degrees of Fennoscandia with existing 1D SSSCs in Fennoscandia and to test consistency with new 3D SSSCs at stations in central Europe. The comparison tests show 1) whether new 3D SSSCs in Fennoscandia might replace old 1D SSSCs and 2) whether the new 3D SSSCs in central Europe are consistent with past experience and existing or new Fennoscandia SSSCs.

3.2 Group-2 GT0-GT10 Reference Events

The Group-2 Consortium Reference Event Database consists of GT0-GT10 events in our study region (Bondár et al. 2001). These events include nuclear explosions, chemical explosions (e.g. identified with the size of the mine or quarry less than 5 km), and well-located earthquakes, particularly from HDC/JHD cluster analyses (e.g. Engdahl and Bergman, 2001). Arrival data are collected from the PIDC REB, NEIC and ISC/EHB bulletins as well as national and local network bulletins in the region. Arrival data include phases recorded at IMS stations, IMS surrogate stations, as well as many other stations in the region.

Our major test data set is built using the GT0-GT10 events with at least three Pn/Sn defining arrivals. A site table was compiled for the relevant stations to include consistent station name and coordinate information. Stations with conflicting station codes/coordinates from the NEIC standard are assigned new names by appending postfixes to the station codes. When specific phase classifications are unavailable, phases are renamed from P (and S) type to Pn and Pg (and Sn and Lg) based on the epicentral distances/depths. Measurement errors are inserted in the arrival tables consistent with PIDC practice (e.g. Israelsson et al., 1997) when SNRs are available, or assigned 1.0 s for all phases otherwise. All slowness and azimuth are made non-defining. The data set contains both regional and telesiesmic phases. Figure 6 shows the events in this data set.

Detailed information on defining phases for the Group-2 GT0-GT10 events by GT category is listed below:

GT category	# of events	# of defining phases	# of defining Pn	# of defining Sn
GT0	66	11438	578	136
GT1	86	19640	1323	263
GT2	131	2218	747	322
GT5	317	54505	7874	139
GT10	25	3116	229	0
Total	625	90917	10751	860

The top 15 IMS stations with the largest number of defining Pn and Sn phases for the Group-2 GT0-GT10 events are listed below:

station	# of phases	station	# of phases	station	# of phases	station	# of phases
FINES	300	MLR	71	ZAL	41	SPITS	22
ARCES	287	GERES	57	VRAC	38	BRVK	16
HFS	255	OBN	44	EIL	24	DAVOS	16
NIL	86	ARU	41	MRNI	22		

The objectives of tests using this data set are to 1) validate the 3D regional travel time model and model errors, and 2) validate expected location improvements for a simulated IMS network in the study region using regional and teleseismic arrivals.

3.3 MORT GT10 events

Thirty-five Mid-Ocean Ridge and transform (MORT) earthquakes in the Gulf of Aden and North Atlantic were selected for validation testing (Antolik, 2001) to test the travel time model in regions without GT0-GT5 events. These events were referenced to bathymetry features on the order of 10 km resolutions, and are estimated as GT10. Arrival data are obtained from the EHB catalog for these events. Figure 7 shows the events in this data set.

The objective of using this data set is to validate the regional travel time model and model errors for extended regions (reaching out to the ocean ridge and transform faults).

3.4 Estimated GT5 EHB events

A set of “candidate” GT5 earthquakes were selected from the EHB catalog for the study region based on GT5 selection criteria. Events were then relocated using only phases recorded within 300 km, and over 80% of the events are thought to be GT5 or better. Figure 7 shows these “candidate” GT5 EHB events. These earthquakes are somewhat deeper than the Group-2 GT0-GT10 events (Figure 8).

The objective of tests using this data set is to validate the regional travel time model and model errors using a larger data set. Comparisons are made for relocation results with and without SSSCs. This test is largely a "do no harm" test.

4.0 Comparisons with existing SSSCs in Fennoscandia

The Fennoscandian data set and 1D SSSCs serve as a benchmark. For direct comparisons, in this test we use Pn and Sn SSSCs developed from both the CUB 1.0 Model and the 1D approach given in Yang and McLaughlin (1999). Note that in Yang and Mclaughlin (1999) Pg and Lg SSSCs were also used. The Pn modeling errors for the CUB model are about 1 second larger than the 1D's within 12 degrees and about 0.5-1 second smaller beyond 12 degrees.

In general, the location results for the GT0-5 events are similar when the CUB 1.0 Model and 1D SSSCs are applied. In both cases, 60% of the events are improved relative the to GT location using Pn and Sn SSSCs. There are some differences in error ellipses between the two models; median error ellipse area is 1100 km^2 with 94% coverage for the 1D SSSCs compared to median ellipse area of 1800 km^2 and 99% coverage with 3D SSSCs. Figures 9-10 compare mislocations and coverages with and without SSSCs for the CUB 1.0 Model. The improvement is more significant for low ndef events (Figures 11-12). Figure 13 shows the direct comparison in location between the 1D and CUB models. There are some large differences in Europe (e.g. Poland), but they cannot be further resolved within this data set.

The location results for the CEB events are similar for most of the events when the 3D and 1D SSSCs are applied. The CEB events along the North Atlantic Ridge correlate well with the mapped tectonic features (Figure 14). There are some differences for events in Europe. Three events (two in southern Europe and one in northern Atlantic ridge) were not located using 1D SSSCs, but were located using the 3D SSSCs. This is probably largely due to inaccuracies in the 1D approach at boundaries.

Location results for the NZ events differ when the 3D and 1D SSSCs are applied in comparison with the JHD locations. While 1D and 3D Pn SSSCs are similar, the 3D Sn SSSC values are larger than the 1D Sn SSSC values for Fennoscandian stations. Locations using a JHD algorithm, the Baltic 1D model, the 3D SSSCs, 1D SSSCs, and IASPEI91 for the 1997/08/16 Kara Sea event are all plotted on Figure 15.

The objective of this test was to establish if any significant operational differences would exist between CUB 3D SSSCs and existing 1D SSSCs for Fennoscandia. No such significant differences could be found. The new 3D SSSCs perform similarly to the existing 1D SSSCs in Fennoscandia. The results of these tests indicate that there should be no impact in replacing the existing 1D SSSCs with 3D SSSCs in Fennoscandia. Replacement of old 1D SSSCs in Fennoscandia with a consistent set of 3D SSSCs for all of Europe would do no harm and all SSSCs would be based on a consistent 3D model.

5.0 Model validation testing

Our major model validation testing is conducted using the Group-2 GT0-GT10 reference events. Events are relocated using only Pn and Sn phases, with and without SSSCs at all available stations in the region. Depth is fixed to zero since all the events are crustal (Figure 8). To be complete and objective, at this stage we include all events and arrivals in the evaluation. The relocation results may be affected by the fact that we do not use any stations outside the study region (-20 to 80 degrees latitude, -40 to 100 degrees longitude; Figure 1), and therefore events near the boundary of the study region may be poorly located due to poor network geometry. For extended coverage of the study region, MORT events (GT10) and candidate GT5 EHB events are included.

5.1 Validation testing using Group-2 GT0-GT10 events

A total of 571 GT0-GT10 events are relocated using Pn and Sn phases, with and without SSSCs, from all available stations. Figure 16 shows Pn and Sn paths used in relocation. Since this relocation used Pn and Sn phases only, many locations are based on only a few poorly distributed stations with large azimuthal gap and/or limited range of distances. Table 1 shows separate evaluation metrics broken down by GTX categories.

When calibrations are applied to 571 GT0-GT10 reference events:

- 60% events are improved, and 47% are improved by more than 20%; compared to 40% events are deteriorated, and 31% deteriorated by more than 20%.
- The median improvement in mislocation is 7.9 km compared to the median deterioration in mislocation of 6.4 km.
- 100% of events have reduced error ellipses. Median ellipse area is reduced 51%, from 4600 to 2240 km^2.
- The median mislocation improved by only 14% (16.5 to 14.1 km). It is statistically significant at 95% level.
- 63% of GT0 events were improved. 58% of the GT0 improved by more than 20% compared to only 28% of the GT0 events deteriorated by more than 20%.
- 46% more events (C1+C2=41 vs. C1+C3=28) were located within GT accuracy.
- 34 events moved from outside to inside GTX accuracy compared to 21 events moved from inside to outside GT accuracy.
- 14% more events located within 18 km (D1+D2=361 vs D1+D3=317).
- The 80th percentile mislocation decreased 33% (from 43 km to 29 km).
- 90% ellipse coverage reduced from 97% without SSSCs to 91% with SSSCs.
- Coverage was closer to the to theoretical χ^2 distribution for the 20th, 50th, 80th and 90th percentiles.
- 74 more events satisfied the Trinity criteria (increase from 11% to 24%) (error ellipse area < 1000 km^2, covers GT, mislocation < 25 km).
- Origin time errors were reduced for 99% of events. The median improvement, relative to the "GT" origin time, is 0.8 seconds (26%).

- Standard error of observations improved for 61% events with a median improvement of 0.2 seconds (17%).

For all 571 GT0-GT10 events (57 GT0 events) we summarize the following classes of events:

with SSSCs	**without SSSCs**	
	within GT accuracy	**beyond GT accuracy**
within GT accuracy	C1=7	C2=34
beyond GT accuracy	C3=21	C4=452
	within 18 km	**beyond 18 km**
within 18 km	D1=264	D2=97
beyond 18 km	D3=53	D4=157

As shown in Table 1, relocation results are similar between all GT0-GT10 events and the subset of GT0-GT5 events, since there are only 25 GT10 events (all in the Aden and Koyna clusters). In the following Sections of this report we will only list statistics for all GT0-GT10 events, given the small differences with and without the GT10 events. Mislocation results are better for GT0-GT2 events than for GT5 events (improvement/deterioration are 9.6/6.4 km for GT0-GT2 events, and 5.5/5.9 km for the GT5 events).

Figure 17 compares mislocations with and without SSSCs by GTX category. Overall mislocations are reduced with SSSCs, particularly in the tails of the distribution. There are some large improvements for GT0-GT1 events. Figure 18 shows that there are also some large mislocations, both with and without SSSCs, for events with low ndef, large azimuthal gap (azgap), minimum distance (mindist), and/or poor station geometry. Event locations are better for events with ndef > 4, azgap < 200 degrees, and/or ellipses elongated less than 5 times of the semi-minor axis. Very often events with small ndef tend to have large azgap, but events with large ndef may also have large azgap. While the scattering is large, there are some large location improvements for low ndef events using SSSCs (Figure 19). Figure 20 shows mislocation improvement scaled by GT accuracy where GT0 events are assigned a 1 km uncertainty. About 31% of the events moved only within GT accuracy or less than 1 km. 40% more events are improved than deteriorated. Histograms of mislocation improvements, both scaled and unscaled, are also given.

Figure 21 shows comparisons of the coverage parameter (mislocation normalized to the error ellipse), with and without SSSCs, by GTX category, compared to the χ^2 distribution. The coverage statistic is χ^2 distribution with an expected 90th percentile of 1. It measures how well the 90% error ellipse covers the GT location. There are large deviations from the expected values, particularly for the uncalibrated case. The single point comparison of the 90% coverage parameter is above 90% both with and without SSSCs. Coverage is generally better than expected below the 90th percentile and worse above the 90th percentile. This indicates that *a priori* errors are over estimated for the majority of events but under estimated for a small number of events. Figure 22 shows the coverage parameter as a function of ndef, azgap, mindist, and station geometry. The coverage becomes somewhat worse for large ndef, small azgap, and good station geometry due to smaller ellipses. This is consistent with location sensitivity to outliers for small azgap, small ndef, large mindist and other indicators of poor station geometry. As shown in Figure 23, with SSSCs there are large ellipse area reductions for events with low ndef, large azgap, and large minimum distance. Figures 24-25 shows comparisons on origin times, origin time errors, and standard errors of observations with and without SSSCs.

Median coverage was 0.1, significantly less than the expected value of 0.3 (off by 67%), indicating that the majority of events were actually located closer to GT than should be expected from the model and measurement errors. The 90 percentile coverage was 0.9, close to the expected value of 1.0 (off by 10%), demonstrating that the 90% error ellipses were indeed "honest". However, the number of outliers (18 events with coverage larger than 2) clearly exceed the expected number at a high significance level (5 events). This indicates that the underlying "Gaussian statistics" for model and measurement error are probably inadequate for this data set. The modeling errors appear to be a conservative compromise under the condition that 90% error ellipses are "honest". However, in order to predict "honest" 95% or 98% error ellipses the modeling errors would need to be inflated. Given the error model, 50%-60% of the time the location procedure performs better than should be expected.

An analysis was performed of the expected degradation versus improvement at selected test coverage values conditioned on the performance of the reference event data set and the total model error (GTX + measurement + model). At every level of test coverage (E* = 0.1 to 2.0), the expected number of events that got significantly worse is never more than should be expected by random chance. For example, we show the analysis for a test coverage value of E* = 0.3. 56% of events are covered by the test ellipse either calibrated or uncalibrated. 18% are uncovered either calibrated or uncalibrated. 8% are covered uncalibrated but uncovered calibrated. 17% are covered uncalibrated but uncovered calibrated. The percentage of events degraded (8%) is actually only half of what we would have expected (26% of 64% = 16%) by random chance. When we define significant improvement/degradation as a function of the test value, E*, we find that more events improve than degrade at all values.

E* = 0.3	**571 Events**	**without SSSCs (Uncalibrated)**		
		E1 > E* Uncovered	**E1 < E* Covered**	
with SSSCs (Calibrated)	**E2 > E* Uncovered**	**18%**	**8% (Degraded)**	**26%**
	E2 < E* Covered	**17% (Improved)**	**56%**	**74%**
		36%	**64%**	**100%**

E*	**% Degraded (E1-E2 > E*)**	**% Improved (E1-E2 < E*)**	**Improved/ Degraded**
0.1	**20**	**34**	**1.68**
0.3	**12**	**20**	**1.64**

0.5	**8**	**15**	**1.85**
0.7	**7**	**10**	**1.36**
0.9	**5**	**5**	**1.00**
1.0	**5**	**5**	**1.00**
2.0	**2**	**2**	**1.22**

We examined the subset of GT0-GT10 events derived from the HDC cluster analysis (Engdahl and Bergman, 2001). About half of the GT5 events are from cluster analysis, but the location accuracy of these events is not homogenous. Original reference events were used to constrain (fix) each cluster. Some well located events within the clusters were promoted to "GT5". Table 2 shows separate evaluation metrics for the original references events and the reference events derived from cluster analysis. When calibrations are applied to the original reference events, over 75% are improved by a median 10-13 km (about 56% reduction) and less than 25% are deteriorated by 7 km. In comparison, when we dilute the highest quality data set with derived reference events, only 62% are improved by a median 8 km and almost 40% are deteriorated by 6-7 km.

Figure 25 shows mislocations of GT0-GT10 events with and without Pn and Sn SSSCs. Mixed relocations results in regions where some events are improved but some are deteriorated indicate inconsistencies in data observations and/or model predictions. Further discussions on mislocations are given in Section 7. Examples of the relocated events are shown in Figures 26-32 where a pair of figures are given for each region, including station-event paths and location comparison with and without SSSCs. The complete set of event relocation figures will be made available at the Consortium web site (http://g2calibration.cmr.gov).

The CUB 1.0 Model based SSSCs and model errors performed well w.r.t. IASPEI.

- **More events were better located.**
- **Fewer events were worse located.**
- **More events were located closer to GT.**
- **Origin times were closer to GT.**
- **General misfit was reduced.**
- **Degradation is less than expected from the error model and test data set.**
- **Model errors predicted "honest" 90% error ellipses.**
- **Model errors may be over conservative for 50% of events but under estimated for 5% of events.**
- **IASPEI91 travel time tables performed better than should be expected given the current IDC model errors.**

5.2 Validation testing using MORT GT10 events

We test using MORT GT10 events to extend path coverage into the ocean basins (Figure 33). No GT0-5 events are available in the ocean basins. Comparisons are made for relocation results with and without SSSCs when using Pn and Sn phases for all stations (Table 3). A total of 24 MORT GT10 events are relocated. There are 342 defining phases, including 307 Pn and 35 Sn phases.

- All 24 events are in the C4 and D4 classes.
- 58% of events are improved by a median 8.9 km, and 42% of events are deteriorated by a median 71.2 km (Figure 34a).
- A significant number of events have large mislocations compared to the results without SSSCs. The large deterioration occurs in the tails (the bad get much worse). At the 80th percentile, the mislocations are 142 km without SSSCs and 185 with SSSCs.
- Error ellipse area is reduced by 4680 km^2 (from 8620 without to 3940) consistent with the smaller model error.
- The ellipse coverage is poor. 90% coverage is reduced from 67% to 46% (Figure 35a).
- 90% coverage parameters with and without SSSCs are much larger than the theoretical χ^2 distribution. Both 90% coverage with and without SSSCs are similar within the 40th percentile, but twice the expected values. Beyond the 50th percentiles the coverage parameters with SSSCs are twice as large as the uncalibrated case.

We also relocated MORT events using a fixed depth of 10 km (Table 3), and the percentage of improved events and coverage are similar to the zero depth case. The mislocations are larger and origin times are improved.

It was observed in the relocation tests that Pn and Sn SSSCs travel-time residuals were generally reduced at less than 15 degrees but increased beyond 15 degrees. It is likely that some of the Pn phases are misassociated P phases. To test this hypothesis, we relocated MORT events using arrivals within 15 degrees and 15 events were relocated (Table 3).

- The median mislocation is from 98.6 km to 82.2 km (Figure 34b).
- 80% events are improved by a median 21.5 km, and 20% events are deteriorated by a median 10.8 km. 40% events are improved by 20% or more, compared to 7% deteriorated by 20% or more.
- Median error ellipse areas reduced from 22000 to 12430 km^2.
- 90% coverages are reduced from 87% to 73% (Figure 35b).
- The median 90% coverage parameters with and without SSSCs are similar to the expected values, but larger beyond the 50th percentile.

Figures 36-37 show the locations of GT10 MORT events relocated using Pn and Sn phases from all stations within 15 degrees, with and without SSSCs. Most events are closer to the Mid-Ocean Ridge with SSSCs than without calibration.

Relocation tests using the MORT GT10 events reveal the strong sensitivity of location algorithms to outliers in the distance range of 15 to 20 degrees due to misassociation of P to Pn. Given the limited number of 15 MORT events that could be located with arrivals under 15 degrees, the test shows only marginal improvement in locations consistent with a "do no

harm" conclusion. The percentage of events that failed the 90% coverage test is only slightly below what could be expected based on the sample size.

5.3 Validation testing using candidate GT5 events from the EHB bulletin

We relocated 435 candidate GT5 events using EHB Pn and Sn phases from all stations in the study region (Figures 33, 38-42; Table 4). There are 53,200 defining phases, including 41,500 Pn and 11,700 Sn phases. Depth was constrained to zero.

- 53% of events are improved by a median 1.7 km, and 47% of the events are deteriorated by a median 1.8 km.
- 162 (C1+C2) events located within 5 km compared to 157 (C1+C3) events without calibration.
- 90% coverage reduced from 94% to 84%.
- Median coverage is at the expected value of 0.3.
- Median error ellipse areas are reduced, from 235 to 100 km^2.

Location results show small improvement in mislocation with SSSCs. Error ellipse areas are reduced consistent with the reduced model error. We also relocated events by fixing the depth to 10 km. The results are similar to the zero depth case except for expected origin time shifts.

with SSSCs	**without SSSCs**	
	within GT accuracy	**beyond GT accuracy**
within GT accuracy	C1=130	C2=32
beyond GT accuracy	C3=27	C4=225
	within 18 km	**beyond 18 km**
within 18 km	D1=384	D2=0
beyond 18 km	D3=8	D4=21

This reference event data set has poor resolving power to demonstrate improvement; a large fraction of events are very well located compared to the estimated GT location uncertainties (5 km) with or without calibration. 384 events (88%) are located within 18 km with or without SSSCs. 130 events (30%) are located within 5 km with or without calibration.

The test results show the 3D SSSCs "do no harm" to locations. This reference event data set has poor resolving power to demonstrate improvement. While the model error under predicts at the 90th percentile error, it correctly predicts the 50th percentile coverage.

6.0 IMS improvement validation testing using Group-2 GT0-GT10 events

IMS location improvement is simulated using the Group-2 GT0-GT10 events with IMS stations and IMS surrogate stations. To further assess the effect of SSSC calibrations in operational event location, five different cases are examined:

- Calibrated Pn and Sn phases only
- Calibrated Pn and Sn phases and uncalibrated Pn and Sn phases
- Calibrated Pn and Sn phases and uncalibrated Pg and Lg phases
- Calibrated Pn and Sn phases and uncalibrated teleseismics phases
- Calibrated Pn and Sn phases and uncalibrated Pn, Sn, Pg, Lg, and teleseismic phases

The first case is for calibrated phases only and the other four are for mixing calibrated with uncalibrated phases. In each case there are two runs, using IMS stations only, and IMS plus IMS surrogate stations. For each case we only use events with at least three defining Pn/Sn phases. As in Section 5, depth is fixed to zero in the relocation, and all events are included in the evaluation. For each case location results with and without SSSCs are compared.

6.1 Calibrated Pn and Sn phases only

Only a partial data set can be used in this test (Table 5) since significantly fewer stations are included (Figure 4), compared to the previous Section (Figure 3).

A total of 240 GT0-GT10 events were relocated using IMS stations only (including 30 GT0 events) with and without SSSCs:

- 62% of events improved by a median 7.6 km compared to 38% deteriorated by a median 8.0 km.
- 49% of the events are improved by 20% or more compared to 31% deteriorated by 20% or more.
- 90% error ellipse coverage reduced from 100% to 98%.

The statistics are similar to the previous cases where all stations are used (Section 5.1; Table 1), but the median deterioration is slightly larger. Some events are poorly located because fewer defining phases are applied, azimuthal gaps are large, and station geometry is poor. The mislocation distribution for this test set of 240 events limited to the IMS stations is not distinguishable from the larger set of 571 events using all stations. For example, 20% of the events are mislocated more than 41 km without calibration compared to 32 km with calibration (22% reduction). These numbers are not statistically significantly different from the 80th percentiles of the larger data set. Again, the most important improvements occur in the tails of the mislocation distribution. When we consider the non-parametric statistics; 38% (C1+C2=11 vs. C1+C3=8) more events are located within GTX accuracy with calibration, 19% (D1+D2=150 vs. D1+D3=126) more events are located within 18 km with calibration. Calibration does more improvement and less harm than no calibration. These results demonstrate SSSCs should improve locations based on regional data for a limited IMS network.

A total of 318 GT0-GT10 events were relocated using IMS plus IMS surrogates (34 GT0 events) with and without SSSCs:

- 59% of events improved by a median 8.2 km compared to 41% deteriorated by a median 6.2 km.
- 46% of the events are improved by 20% or more compared to 30% deteriorated by 20% or more.
- 90% error ellipse coverage reduced from 98% to 97%.

with SSSCs	without SSSCs (IMS)		without SSSCs (IMS/surrogate)	
	within GT accuracy	**beyond GT accuracy**	**within GT accuracy**	**beyond GT accuracy**
within GT accuracy	C1=0	C2=11	C1=3	C2=16
beyond GT accuracy	C3=8	C4=187	C3=13	C4=252
	within 18 km	**beyond 18 km**	**within 18 km**	**beyond 18 km**
within 18 km	D1=104	D2=46	D1=140	D2=47
beyond 18 km	D3=26	D4=60	D3=22	D4=109

When the SSSCs are applied for existing IMS stations and surrogates in the study region (Figure 4), more than half of the events in the data set are relocated (Table 5). Similarly to the results using all stations (Section 5.1; Table 1), 59% events are improved by 8.2 km and the rest are deteriorated by 6.2 km. Almost all error ellipses are reduced with about 60% deduction while maintaining almost the same 90% coverage.

Again, the mislocation distribution for this test set of 318 events limited to the IMS and surrogate stations is not distinguishable from the larger set of 571 events using all stations. The mislocation 80th percentile is reduced 30% (from 53 to 37 km), 18% (C1+C2=19 vs. C1+C3=16) more events are located within GTX accuracy, 3 events are located within GTX accuracy with or without calibration, 15% (D1+D2=187 vs. D1+D3=162) more events are located within 18 km.

We also tested the SSSC effect on event location use only about 35 unique IMS/surrogate stations, i.e. only one station is used for the data set if multiple surrogates are available for an IMS station. Fewer events are able to relocate but the results are similar (Table 5). In the following Sections of this report we use these unique stations for IMS/surrogates testing in order to eliminate side effects from using multiple surrogates for some stations.

These test results demonstrate SSSCs should improve locations based on regional data for a fuller IMS network Calibration does more improvement and causes less harm than no-calibration.

6.2 Mixing calibrated Pn and Sn phases with uncalibrated Pn and Sn phases

We next evaluate the effect of mixing calibrated and uncalibrated Pn and Sn phases in event location. The GT0-GT10 events are located using all stations in the study region, with and without SSSCs for IMS stations and IMS/surrogates (Table 6). Using SSSCs for IMS stations only and IMS plus IMS surrogates, 246 and 340 events were relocated respectively. Using IMS stations only, 58% of events are improved by a median 4.9 km, compared to 42% events deteriorated by a median 3.8 km. Using IMS and IMS surrogate stations, 54% events are improved by a median 5.5 km, compared to 46% events deteriorated by a median 5.1 km. In both cases the error ellipse area is reduced with similar 90% coverage (97% without SSSCs vs. 96% with SSSCs). Compared to the previous case where only calibrated Pn and Sn were utilized, the location improvement and, in particular, deterioration are smaller. Adding uncalibrated Pn and Sn phases generally improved location performance.

A total of 246 GT0-GT10 events are relocated (32 GT0 events) using calibrated and uncalibrated Pn and Sn phases with and without SSSCs for IMS stations; 340 events (34 GT0 events) for IMS/surrogates:

with SSSCs	**without SSSCs (IMS)**		**without SSSCs (IMS/surrogates)**	
	within GT accuracy	**beyond GT accuracy**	**within GT accuracy**	**beyond GT accuracy**
within GT accuracy	C1=4	C2=11	C1=4	C2=14
beyond GT accuracy	C3=13	C4=186	C3=17	C4=271
	within 18 km	**beyond 18 km**	**within 18 km**	**beyond 18 km**
within 18 km	D1=145	D2=31	D1=192	D2=47
beyond 18 km	D3=21	D4=49	D3=29	D4=72

For the IMS case 59% events are located within 18 km with and without SSSCs. 176 vs. 166 events (D1+D2 vs. D1+D3) are located within 18 km with and without SSSCs, respectively. For the IMS/surrogate case 56% events are located within 18 km with and without SSSCs. 239 vs. 221 events (D1+D2 vs. D1+D3) are within 18 km with and without SSSCs, respectively. Similar to the calibrated Pn and Sn only case (Section 6.1; Table 5), large improvement occurred in the mislocation tails. At the 80th percentile there is a 23% reduction in mislocation (from 27 to 22 km) for the IMS station case, and 21% reduction (from 29 to 24 km) for the IMS/surrogate case.

The results of this test indicate that mixing calibrated and uncalibrated regional phases in the IMS network does not do significant harm. The improvements in calibration are only generally diluted.

6.3 Mixing calibrated Pn and Sn phases with uncalibrated Pg and Lg phases

This test combines uncalibrated Pg and Lg phases with calibrated Pn and Sn phases. Events are located with and without SSSCs for IMS regionals and IMS/surrogates, respectively (Table 7). This simulates the IMS network with the CUB 1.0 Model Pn and Sn SSSCs installed but without Pg and Lg SSSCs installed.

When events are located using calibrated Pn and Sn phases and uncalibrated Pg and Lg regionals for IMS stations (Table 7), 56% of the events are improved by a median 6.1 km and 44% of the events are deteriorated by a median 8.4 km. There are smaller improvements and larger deteriorations compared to those without mixing uncalibrated Pg and Lg arrivals (Section 6.1; Table 5). When events are located using calibrated IMS/surrogate Pn and Sn and uncalibrated Pg and Lg phases for IMS/surrogate stations, 48% of the events are improved by a median s6.7 km and 52% of the events are deteriorated by a median 5.0 km (Table 7). Both improvement and deteriorations are smaller than those without mixing uncalibrated phases (Section 6.1; Table 5). For the IMS case, 57% (D1+D2) events are located within 18 km with and without SSSCs. For the IMS/surrogate case, 184 vs. 173 (D1+D2 vs. D1+D3) events are within 18 km with and without SSSCs, respectively.

A total of 261 GT0-GT10 events are relocated (32 GT0 events) using Pn and Sn phases with SSSCs for IMS stations; 287 events (31 GT0 events) for IMS/surrogates:

with SSSCs	without SSSCs (IMS)		without SSSCs (IMS/surrogates)	
	within GT accuracy	**beyond GT accuracy**	**within GT accuracy**	**beyond GT accuracy**
within GT accuracy	C1=0	C2=12	C1=0	C2=14
beyond GT accuracy	C2=11	C4=206	C2=18	C4=224
	within 18 km	**beyond 18 km**	**within 18 km**	**beyond 18 km**
within 18 km	D1=122	D2=28	D1=140	D2=44
beyond 18 km	D3=29	D4=82	D3=33	D4=70

The results of this test show, that although it is undesirable to mix calibrated with uncalibrated regionals for the same stations, the mixing "does no harm" to event location in such a situation.

6.4 Mixing calibrated Pn and Sn phases with uncalibrated teleseismic phases

Teleseismic phases play an important role in IMS event location processing. We evaluate the effect on event location when unclaibrtaed teleseismic phases and calibrated regional phases are used together in a simulated IMS network. In this set of tests events are located with and without SSSCs for IMS stations and IMS/surrogates, (Table 8).

When events are located using calibrated Pn and Sn phases and uncalibrated IMS teleseismics for IMS stations (Table 8), 63% of the events are improved by a median 6.8 km and 37% events are deteriorated by a median 9.0 km. The improvement is smaller and the deterioration is larger compared to the case without mixing uncalibrated regionals (Section 6.1; Table 5). There are larger improvements and deteriorations compared to those with mixing uncalibrated regionals (Section 6.; Table 7). When events are located using calibrated Pn and Sn phases and uncalibrated IMS teleseismic phases for IMS/surrogate stations, 58% of the events are improved by a median 5.4 km and 42% of the events are deteriorated by a median 7.3 km.

For the IMS case, 18 vs. 5 (C2 vs. C3) events are relocated within GT accuracy with and without SSSCs, respectively (72% increase). 158 vs. 141 (D1+D2 vs. D1+D3) events are located within 18 km with and without SSSCs, respectively. Similar to the calibrated Pn and Sn case (Section 6.1; Table 5), most of the improvement occurs at the mislocation tail. At the 80th percentile, there is a 23% reduction in mislocation with SSSCs (from 35 to 27 km). For the IMS/surrogate case, again more events are better with SSSCs than without (15 vs. 10 for C2 vs. C3, and 204 vs. 193 for D1+D2 vs. D1+D3).

Compared to those cases where no teleseismic phases were used (Section 6.1; Table 5), there are slightly smaller improvements and slightly larger deteriorations due to the large number of teleseismic phases added into event location. However, the distributions of mislocation are not statistically significantly different.

A total of 243 GT0-GT10 events are relocated (30 GT0 events) using Pn and Sn phases with SSSCs for IMS stations; 326 events (32 GT0 events) for IMS/surrogates:

with SSSCs	without SSSCs (IMS)		without SSSCs (IMS/surrogates)	
	within GT accuracy	**beyond GT accuracy**	**within GT accuracy**	**beyond GT accuracy**
within GT accuracy	C1=0	C2=18	C1=3	C2=15
beyond GT accuracy	C3=5	C4=189	C3=10	C4=266
	within 18 km	**beyond 18 km**	**within 18 km**	**beyond 18 km**
within 18 km	D1=108	D2=50	D1=157	D2=47
beyond 18 km	D3=33	D4=52	D3=36	D4=86

The results indicate event location is improved by Pn and Sn SSSCs for simulated IMS networks even with large numbers of teleseismic phases.

6.5 Mixing calibrated Pn and Sn phases with uncalibrated Pg, Lg, and teleseismic phases

In this set of tests we consider all factors that were evaluated separately in Sections 6.1-6.4, including uncalibrated regional and teleseismic phases. This is the probable situation to faced in the current PIDC/IDC system when Group 2 Pn and Sn SSSCs are installed. In this set of tests, events are located with/without SSSCs, using IMS stations only, and IMS/surrogates. In each case we only evaluate events with at least 3 defining Pn and Sn phases (Tables 9-10).

When events are located using calibrated Pn and Sn phases as well as uncalibrated Pg, Lg, and teleseismic phases for IMS stations, 60% of the events are improved by a median 5.5 km and 40% of the events deteriorated by a median 8.6 km (Table 9). 90% ellipse coverage is stable at 96%. Similar to the previous cases when mixing calibrated and uncalibrated data (Sections 6.1-6.4), the improvement is slightly smaller and deterioration is slightly larger than the case without uncalibrated data (Section 6.1).

When events are located using calibrated Pn and Sn phases as well as uncalibrated Pg, Lg, and teleseismics for IMS/surrogates, there is smaller improvement/deterioration (Table 9) than the previous cased when mixing calibrated and uncalibrated data (Sections 6.1-6.4). 90% ellipse coverage is stable at 96%. <u>The location improvement is ambiguous because the large number of teleseismic phases dominate event location.</u> There are more events located within the GT accuracy with SSSCs than without (C1+C2=19 vs. C1+C3=8 for the IMS case, and C1+C2=16 vs. C1+C3=12 for the IMS/surrogate case).

The test results show that the Pn and Sn SSSCs at least “do no harm” in event location when mixed with uncalibrated regional and teleseismic phase in a simulated IMS network. However, the test results from the full set of events did not simulate the situation of a small event detected by the IMS network.

A total of 245 GT0-GT10 events are located using all phases from IMS stations (including 31 GT0 events), and 328 events (32 GT0 events) using IMS/surrogates:

with SSSCs	without SSSCs (IMS)		without SSSCs (IMS/surrogates)	
	within GT accuracy	beyond GT accuracy	within GT accuracy	beyond GT accuracy
within GT accuracy	C1=0	C2=19	C1=3	C2=16
beyond GT accuracy	C3=8	C4=186	C3=12	C4=265
	within 18 km	beyond 18 km	within 18 km	beyond 18 km
within 18 km	D1=126	D2=29	D1=180	D2=35
beyond 18 km	D3=32	D4=58	D3=34	D4=79

We wished to use subset of the data set to simulate the situation where teleseismic phases are not dominant. Small magnitude GT events would be ideal in such testing where there are a fair amount of both regional and teleseismic phases. Since the magnitude information is absent/inaccurate for most events in this data set, we used the teleseismic to regional phase ratio to select a subset of the events for further evaluation. The ratio histograms for the GT0-GT10 events are similar to those for the PIDC REB events during 1995/01/01-2000/12/31 (Figures 43-44). In both cases a large number of events have a teleseismic to Pn and Sn ratios of about 3.

Table 10 shows results for events with teleseismic to Pn and Sn ratios between 1 and 3. Using IMS stations only, over 80% of the events are improved by a median of 6 km, while less than 20% of the events are deteriorated by a median of 10 km. Using IMS and surrogates, 71% of the events are improved by a median 5-7 km, compared to 29% events are deteriorated by a median 1-3 km.

This simulation argues that Pn and Sn SSSCs will improve locations for small events in the IMS network when mixed with uncalibrated regional and teleseismic phases.

7.0 Examinations of poorly located events

In order to gain insight into the outliers in Section 5.1, we examine some of the GT0-GT10 events in the Group-2 data set in greater detail. Besides the effect of poor station geometry, events may be poorly located due to outliers in observations and/or poor model prediction. To separate the effect of data and model as much as possible, we conducted additional relocation tests.

In the first relocation test of this section, the test data set from Section 5.1 was relocated using only Pn arrivals (Table 11). The mislocation statistics are similar to the Pn+Sn case (Table 1; Section 5.1). We compare the relocation results between the Pn only and Pn+Sn cases, without SSSCs, to identify possible problems in Sn phases. We hypothesize that if events are better located with Pn+Sn compared to Pn only, and also better located without SSSCs than with SSSCs, it may indicate problems in the Sn SSSCs or some of the Sn phases may be S phases instead. There are 21 (out of 571) events with Sn phases between 15 and 20 degrees that have extremely large travel-time residuals with SSSCs applied. We renamed these phases from Sn to S and the relocation statistics (Table 11) using Pn and Sn (i.e. these S phases are not used) are also similar to the original case (Table 1; Section 5.1). On the other hand, if events are better located with Pn only, there may be problems with the observed Sn picks. There are 103 events with such suspicious Sn phases. With only Pn SSSCs, 26 of the 103 events are improved and 77 events are deteriorated, compared to 33 events are improved with Pn and Sn SSSCs. Overall the statistics for all events in the data set, after eliminating suspicious Sn phases for the 103 events, are somewhat worse than the Pn+Sn case (Table 11).

For 230 degraded events relocated with Pn and Sn SSSCs as described in Section 5.1 (Table 1),

- 11 events have suspicious Sn phases and they are improved using only Pn phases with SSSCs. Using Pn phase only for these 11 events, the median is 1 km deterioration, compared to the 5.7 km deterioration using both Pn and Sn phases. These are mostly small mining events in Fennoscandia.
- There are 54 events with suspicious Sn picks.18 of these events have Sn phases that might be S instead and locations without them are improved. All 18 events are improved using only Pn SSSCs, better than the improvement when located without these Sn phases only (except for one event). Using Pn phases only for these 18 events, the median is 16.2 km improvement, compared to the 34.1 km deterioration using both Pn and Sn phases. These events are nuclear explosions with arrivals from the EHB catalog. However, the other 35 events may be due to poor model predictions. Locations for the 35 events using Pn and Sn phases are better than the Pn only case without SSSCs, but worse with SSSCs, indicating Sn model predictions may be questionable for these paths. Using Pn phases only for these 35 events, the median is 3.1 km improvement, compared to the 6.2 km deterioration using both Pn and Sn phases. Again, the 35 events are mostly small mining events in Fennoscandia.
- There are 110 events unchanged since Sn phases are absent for these events (except that one event has a small number of Sn phases compared to Pn phases), and 9 events are not located using Pn only.
- For the remaining of 46 events, 3 events have Sn phases that are probably misassociated S phases. Using Pn only for all three events are deteriorated. Two of them are improved when these Sn phases are not used while the other is the same as the Pn case. Using Pn phases only for these 3 events, the median is 67.2 km improvement, compared to the 42.5 km deterioration using both Pn and Sn phases. Again these three events are nuclear explosions with arrivals from the EHB catalog. 43 events are inconclusive. The poor location with SSSCs may be due to poor Sn data or SSSCs. The deterioration for these 43 events is mostly within 5 km. Using Pn phases only for these 43 events, the median is 9.7 km deterioration, compared to the 4.6 km deterioration using both Pn and Sn phases. Again, they are mostly small mining events in Fennoscandia.

In all tests described in this report so far, phase associations are fixed in the location process for direct comparisons of the results with and without SSSCs. However, in the PIDC/IDC processing a outlier rejection procedure is imposed. To explore the effects of the outlier rejection with SSSCs in the true system, we also relocate events, with and without Pn and Sn SSSCs, under the residual constraints. In this test data are ignored with residuals greater than three times the data standard error, i.e. all data with residuals greater than three times the a priori data standard error are disregarded during any given iteration. The results are similar to the previous ones (Table 11).

In addition to events that are compared with and without SSSCs, there are also 3 events located only with Pn and Sn SSSCs but not without SSSCs, although the already very large time residuals are increased with SSSCs. There are also 24 events located without SSSCs but not with SSSCs, although time residuals are reduced. They are mostly events with few stations and large azimuthal gaps.

In this GT0-GT10 data set, the three major data sources are the HDC cluster analysis (about 200 events), small mining events in Fennoscandia (about 170 events), and nuclear explosions (over 100 events). It appears that the Fennoscandian events tend to have poor phase picks, and the nuclear explosion arrivals, from the EHB catalog, tend to have S/Sn association problems. We also examine statistics for the events in this data set without each of these three data sources (Table 12). Compared to the original statistics (Table 1), both the improvement and deterioration are larger without the Fennoscandian events, and smaller without the nuclear explosions. The results without the HDC cluster events are similar to the original case (Table 1).

Poor locations with SSSCs may result from several factors. Poor model predictions may contribute to poor locations for some events. We observe that some stations have inconsistent Pn vs. Sn SSSCs, and/or inconsistent SSSCs compared to neighboring stations (e.g. the Sahara events). These are to be improved in Phase 2 as models are refined and improved. However, it appears that sometimes the location process is somewhat sensitive to SSSCs for events with poor station geometry, as observed in the previous study (Yang et al., 1999). It is unclear why the location without SSSCs are less affected by the azimuthal gaps/questionable phase picks. One possibility is that the phase picks/defining choices were referenced to the IASPEI91 or other global models. Many events might have been picked and located based on the IASPEI91/AK135/JB models, so the phase picks might have been biased by poor model predictions in an effort to get better fits. At this time it is hard to separate the effect between data and models when analyzing location results with and without SSSCs. Further investigation will be valuable in providing insight into the problem. For example, there are abundant GT0-2 events and waveform data in Fennoscandia. An analyst may make phase picks/associations and locate the events using the 1D Baltic model. We can compare the phase picks and locations between the IASPEI91 and the 1D Baltic models, and compare the relocation results with and without SSSCs for the two sets of picks and associations.

8.0 Conclusions and Future Work

Validation testing of the SSSCs was conducted by relocating reference events in the Group-2 study region, with and without SSSCs. In order to validate the model, SSSCs are computed not only for the Group-2 IMS and surrogate stations, but also for additional IMS stations and other available stations in the region. We tested SSSCs for all stations in the study region to validate the model for the entire region and to minimize the situation of mixing calibrated and uncalibrated data in relocating events. This report documents test results of the CUB 1.0 Model only.

Four data sets are used in the offline testing, 1) the Fennoscandian events, 2) Group-2 GT0- GT10 events, 3) MORT events, and 4) candidate GT5 EHB events. The major testing is conducted using the Group-2 GT0-GT10 reference events. For model validation, all stations are used in relocation. For IMS location validation only IMS stations and IMS surrogate stations are used. To separate various factors that affect event location multiple sets of tests are conducted, including relocating events using calibrated regionals only, calibrated regional phases and uncalibrated regional phases, calibrated regional and teleseismic phases, and calibrated regional phases and uncalibrated regional and teleseismic phases. We included all events in our evaluation in order to be objective and to reveal potential problems.

Relocation results using SSSCs show overall improvement in event location and error ellipses. In general low ndef events have larger scatter in improvement/deterioration. When SSSCs are applied for all Pn and Sn phases in relocating the GT0-GT10 events, 60% events are improved in location with a median improvement in mislocation of 7.9 km. All events have reduced error ellipses without losing 90% coverage. The median reduction in ellipse area is 2360 km^2 (from 4600 to 2240 km^2). The improvement is similar when only calibrated IMS/surrogate regionals are used, but deterioration is larger when only calibrated IMS regionals are used due to limited number/geometry of stations. Using IMS/surrogate stations with SSSCs, 59% events are improved by a median 8 km and 41% deteriorated by a median 6.2 km. This test indicates that the event locations can be improved using SSSCs when the IMS network is fully deployed. When mixing calibrated and uncalibrated regionals and uncalibrated teleseismics, results show less improvement in general. Calibrations are less effective when a large number of uncalibrated phases are also used in event location. For events with no more teleseismic phases than 3 times the number of Pn and Sn phases, there is large improvement when located using IMS/surrogate. For events located using IMS/surrogate stations, 67% of events are improved by a median 7.0 km and 33% events are deteriorated by a median 1.1 km when no more than the same number of teleseismics are used. When the number of teleseismics is three-folded, 71% events are improved by a median 5.0 km and 29% events are deteriorated by a median 2.8 km. We expect the Pn and Sn SSSCs will improve small events recorded by an IMS type network using a mixture of calibrated regional and uncalibrated teleseismic phases.

Several lessons have been learned from the validation testing. Improvement on these aspects is expected in Phase 2.

- Despite our effort in collecting GT5 or better events throughout the study region, the event geographic distribution is still limited. As a result, some areas are better validated than others, and some areas are yet to be validated (e.g. North Africa). In Phase 2, more data will be collected for better coverage.

- At present the data quality in our collections is inhomogeneous, even within the same GT category. For instance, within a cluster the original reference events may be better located than the derived events. Relocation results show better improvement for the original reference cluster events when SSSCs are applied. Furthermore, the current GT estimates may change as further data development is carried out. Since the improvement in event location is less than 10 km using SSSCs, it is important to assess the reference events as accurate as possible.

- Mixing calibrated and uncalibrated data in event location dilutes the benefits of calibration, particularly to mixing calibrated and uncalibrated regional phases for a given station. Developing Pg and Lg SSSCs should have a high priority in Phase 2. Teleseismic phase calibrations may also be explored since teleseismic phases play a dominant role in IMS event location.

- The modeling errors currently used are conservative, invariant in azimuth, and station-independent. More realistic modeling errors are expected in Phase 2 that are closely coupled with the 3-D model.

- The reference event origins, arrivals, and station information is collected and merged from a variety of data sources. Currently inconsistencies may still exist in the testing data sets. We will continue our effort in vetting the information for further studies in Phase 2.
- Locations are very sensitive to outliers and misassociation with or without SSSCs when the azimuthal distribution of network is poor. This was previously documented in the Fennoscandia study (Yang and Mclaughlin, 1999). Investigation into this problem is an ongoing effort.
- Compared to previous SSSC studies, the relocation results are similar to those for Fennoscandia (Yang and McLaughlin, 1999), and both are better than those for North America (Yang and McLaughlin, 2000). The current tests have only used Pn and Sn SSSCs while Pg and Lg SSSCs were used in the two other regions. Pg and Lg SSSCs will be included in Phase 2 testing.
- We show statistics in this report for all events in the test set. This includes many events along the border of the study region, which may be poorly located since we only use regional phases from stations within the study region. Other strategies may be explored in Phase 2.

9.0 References

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Table 1: Evaluation metrics for relocation of all GT0-GT10 events using all regional Pn and Sn SSSCs (Section 5.1)

	All events (GT0-10)	All events (GT0-5)	All events (GT0-2)	All events (GT5)
GT category	GT0-GT10	GT0-GT5	GT0-GT2	GT5
time period	5/1/1962-9/5/ 2000	5/1/1962-7/18/ 2000	5/1/1962-7/18/ 2000	10/25/1964-4/21/ 2000
number of events (C0;C1;C2;C3;C4) (D1;D2;D3;D4)	571 (57;7;34;21;452) (264;97;53;157)	548 (57;7;34;18;432) (261;96;53;138)	272 (57:0:7:5:203) (112:58:25:77)	276 (0:7:27:13:229) (150:38:27:61)
median mislocation (km)	from 16.5 to 14.1	from 15.9 to 13.6	from 17.7 to 15.0	from 13.2 to 11.9
20,40,60,80 percentiles with-out and with SSSCs (km)	8;13;22;43 6;11;17;29	8;12;20;41 6;10;16;28	8;14;25;49 6;11;17;30	8;12;17;27 6;10;15;26
% of events improved on GT distance (C0;C1;C4) median improvement (C0;C1;C2;C4)	60% (63%; 71%; 59%) 7.9 km (9.1; 0.9; 6.0; 8.0)	60% 7.6 km	61% 9.6 km	59% 5.5 km
% of events deteriorated on GT distance (C0;C2;C4) median deterioration (C0;C1;C3;C4)	40% (37%;29%;41%) 6.4 km (8.1; 1.4; 5.2; 6.6)	40% 6.3 km	39% 6.4 km	41% 5.9 km
% of events improved on GT distance by more than 20% (C0;C1;C2;C4)	47% (58%; 57%; 97%;44%)	47%	49%	46%
% of events deteriorated on GT distance by more than 20% (C0;C1;C3;C4)	31% (28%; 29%; 100%; 31%)	31%	29%	33%
% of events improved on error ellipses median improvement (sqkm)	100% 2100 (from 4600 to 2240)	100% 2000 (from 4300 to 2150)	100% 2600 (from 5620 to 3000)	99% 1000 (from 1930 to 900)
90% ellipse coverage	from 97% to 91%	from 97% to 90%	from 97% to 93%	from 96% to 88%
20,50,80,90 percentiles with-out and with SSSCs	0.02;0.07;0.3;0.5 0.02;0.09;0.5;0.9	0.02;0.07;0.3;0.5 0.02;0.08;0.4;1.0	0.01;0.07;0.3;0.5 0.01;0.07;0.4;0.7	0.02;0.07;0.3;0.5 0.02;0.1;0.5;1.2
TRINITY	from 11% to 24%	from 11% to 25%	from 2% to 9%	from 20% to 42%
% of events improved on origin time error median improvement	99% 0.8 s (from 3.1 to 2.2)	99% 0.7 (from 3.0 to 2.2)	99% 0.8 (from 3.8 to 2.7)	99% 0.6 s (from 1.8 to 1.2)

Table 1: Evaluation metrics for relocation of all GT0-GT10 events using all regional Pn and Sn SSSCs (Section 5.1)

	All events (GT0-10)	All events (GT0-5)	All events (GT0-2)	All events (GT5)
% of event improved on standard error of observations **median improvement**	61% 0.2 (overall from 1.2 to 1.1)	61% 0.2 (overall from 1.2 to 1.1)	-	71% 0.2 (overall from 1.3 to 1.1)

Table 2: Evaluation metrics for relocation of all HDC events using all regional Pn and Sn SSSCs (Section 5.1)

	HDC only (GT5-10)	**HDC only (GT5)**	**reference HDC only (GT5-10)**	**reference HDC only (GT5)**
GT category	GT5-GT10	GT5	GT5-GT10	GT5
time period	12/10/1967-9/5/2000	9/22/1969-12/13/1999	3/11/1975-9/2/2000	3/11/1975-11/19/1999
number of events (C0;C1;C2;C3;C4) (D1;D2;D3;D4)	192 (0;0;21;14;175) (93;26;14;68)	169 (0;0;21;11;155) (90;35;14;49)	71 (0;0;8;4;52) (32;12;0;19)	58 (0;0;8;4;43) (32;11;0;11)
median mislocation (km)	from 17.7 to 14.9	from 16.6 to 12.9	from 22.9 to 12.9	from 17.2 to 10.0
% of events improved on GT distance median improvement	62% 8.0 km	63% 7.6 km	75% 12.6 km	76% 10.8 km
% of events deteriorated on GT distance median deterioration	38% 6.8 km	37% 6.3 km	26% 6.9 km	27% 6.9 km
% of events improved on GT distance by more than 20%	49%	50%	62%	61%
% of events deteriorated on GT distance by more than 20%	32%	30%	18%	20%
% of events improved on error ellipses median improvement (sqkm)	100% 1000 (from 1830 to 830)	96% 840 (from 1520 to 680)	99% 1550 (from 3080 to 1500)	98% 1210 (from 2370 to 1130)
90% ellipse coverage	from 96% to 86%	from 96% to 84%	from 97% to 97%	from 97% to 97%
20,50,80,90 percentiles without and with SSSCs	0.04;0.1;0.3;0.5 0.04;0.2;0.8;1.3	0.03;0.1;0.3;0.4 0.03;0.1;0.7;0.1.4	0.04;0.08;0.3;0.6 0.02;0.09;0.3;0.6	0.02;0.07;0.3;0.4 0.01;0.08;0.3;0.4
TRINITY	from 16% to 40%	from 18% to 45%	from 17% to 39%	from 20% to 45%
% of events improved on origin time error median improvement	99% 0.5 s (from 1.7 to 1.2)	99% 0.5 s (from 1.5 to 1.0)	97% 0.8 s (from 2.6 to 1.8)	97% 0.8 s (from 2.5 to 1.7)
% of event improved on standard error of observa-tions median improvement	82% 0.2 (from 1.6 to 1.4)	84% 0.2 (from 1.6 to 1.4)	77% 0.3 (from 1.4 to 1.1)	79% 0.3 (from 1.5 to 1.2)

Table 3: Evaluation metrics for relocation of MORT events using regional Pn and Sn SSSCs only and with teleseismics (Section 5.2)

	Pn and Sn SSSCs only	Pn and Sn within 15 degrees	Pn and Sn SSSCs only (depth=10 km)
GT category	GT10	GT10	GT10
time period	02/11/78-05/26/95	11/16/78-10/12/93	02/11/78-05/26/95
number of events	24	15	24
median mislocation (km)	from 53.6 to 57.6	from 98.6 to 82.2	from 68.1 to 79.5
20,40,60,80 percentiles without and with SSSCs (km)	35;61;88;142 32;55;103;185	37;58;102;389 27;59;94;254	35;60;84;141 30;55;99;188
% of events improved on GT distance median improvement	58% 8.9 km	80% 21.5 km	58% 14.2 km
% of events deteriorated on GT distance median deterioration	42% 71.2 km	20% 10.8 km	42% 50.9 km
% of events improved on GT distance by more than 20%	29%	40%	29%
% of events deteriorated on GT distance by more than 20%	38%	7%	38%
% of events improved on error ellipses median improvement (sqkm)	100% 4680 (from 8620 to 3940)	100% 13100 (from 22000 to 12430)	100% 6400 (from 12600 to 5500)
90% ellipse coverage	from 67% to 46%	from 87% to 73%	from 67% to 46%
20,50,80,90 percentiles without and with SSSCs	0.3;0.4;2.2;3.7 0.2;0.8;5.4;7.8	0.06;0.2;0.8;1.4 0.06;0.3;1.1;1.4	0.3;0.6;2.2;3.6 0.2;1.4;5.6;7.9
TRINITY	from 0% to 0%	from 0% to 0%	from 0 to 0
% of events improved on origin time median improvement	54% deteriorated 5.9 deterioration (overall from 5.2 to 3.8)	-	67% deteriorated 2.6 (overall from 2.7 to 4.4)
% of events improved on origin time error median improvement	100% 1.7 (overall from 7.6 to 5.3)	100% 4.3 (from 12.0 to 8.3)	100% 2.5 (overall from 7.6 to 5.3)
% of event improved on standard error of observations median improvement	-	-	-

Table 4: Evaluation metrics for relocation of EHB events using regional Pn and Sn SSSCs only and with teleseismics (Section 5.3)

	Pn and Sn SSSCs for all stations	**Pn and Sn SSSCs for all stations (depth=10 km)**
GT category	GT5	GT5
time period	5/12/74-12/29/99	5/12/74-12/29/99
number of events (C1;C2;C3;C4) (D1;D2;D3;D4)	435 (130:32:27:225) (384:0:8:21)	435
median mislocation(km)	from 7.8 to 7.5	from 7.7 to 7.7
20,40,60,80 percentiles without and with SSSCs (km)	4;7;9;13 4;7;8;12	4;7;9;13 4;7;9;12
% of events improved on GT distance (C1;C4) median improvement (C1;C2;C4)	53% (44%:41%) 1.7 km (0.8:2.4:1.7)	52% 2.1 km
% of events deteriorated on GT distance (C1;C4) median deterioration (C1;C3;C4)	47% (56%:59%) 1.8 km (0.7:3.1:2.0)	48% 1.9 km
% of events improved on GT distance by more than 20% (C1;C2;C4)	31% (27%:85%:16%)	30%
% of events deteriorated on GT distance by more than 20% (C1;C3;C4)	30% (36%:96%:31%)	31%
% of events improved on error ellipses median improvement (sqkm)	100% 130 (overall from 235 to 100)	100% 130 (overall from 240 to 100)
90% ellipse coverage	from 94% to 84%	from 93% to 83%
TRINITY	from 81% to 76%	from 80% to 75%
% of events improved on origin time median improvement	60% deteriorated 0.6 s (overall from 0.7 to 0.9)	89% deteriorated 0.9 s (overall from 1.1 to 2.0)
% of events improved on origin time error median improvement	100% 0.2 s (overall from 0.7 to 0.5)	100% 0.2 s (overall from 0.7 to 0.5)
% of event improved on standard error of observations median improvement	-	62% 0.1 s (overall from 2.7 to 2.7)

Table 5: Evaluation metrics for relocation of all GT0-GT10 events using regional Pn and Sn SSSCs for IMS stations only and for IMS+surrogates (Sections 6.1)

	IMS only	**IMS+surrogates**	**IMS+surrogates (unique)**
GT category	GT0-GT5	GT0-GT10	GT0-GT10
time period	9/6/1988-7/18/2000	9/26/1969-7/18/2000	9/26/1969-7/18/2000
number of events (C0;C1;C2;C3;C4) (D1;D2;D3;D4)	240 (30;0;11;8;187) (104;46;26;60)	318 (34;3;16;13;252) (140;47;22;109)	285 (31;13;16;225) (124;53;30;78)
median mislocation (km)	from 16.2 to 14.2	from 17.1 to 15.3	from 16.4 to 14.9
20,40,60,80 percentiles without and with SSSCs (km)	7;13;21;41 7;12;18;32	7;13;25;53 7;13;19;37	7;13;21;42 7;12;17;29
% of events improved on GT distance median improvement	62% 7.6 km	59% 8.2 km	58% 8.4 km
% of events deteriorated on GT distance median deterioration	38% 8.0 km	41% 6.2 km	42% 6.2 km
% of events improved on GT distance by more than 20%	49%	46%	45%
% of events deteriorated on GT distance by more than 20%	31%	30%	32%
% of events improved on error ellipses median improvement (sqkm)	99% 3750 (from 10250 to 6010)	99% 3100 (from 8800 to 5100)	99% 3060 (from 7520 to 4310)
90% ellipse coverage	from 100% to 98%	from 98% to 97%	from 99% to 98%
TRINITY	from 0% to 1%	from 0% to 5%	from 0% to 1%
% of events improved on origin time error median improvement	98% 0.9 s (from 4.4 to 3.6)	97% 0.8 s (from 4.2 to 3.5)	98% 0.8 (from 3.9 to 2.8)
% of event improved on standard error of observations median improvement	51% 0.4 (overall from 0.6 to 0.4)	55% 0.8 (overall from 0.7 to 0.6)	55% 0.3 (overall from 0.7 to 0.6)

Table 6: Evaluation metrics for relocation of all GT0-GT10 events using Pn and Sn SSSCs for IMS stations only and for IMS+surrogates, along with uncalibrated Pn and Sn phases (Section 6.2). All stations are used.

	IMS only	**IMS+surrogates**
GT category	GT0-GT10	GT0-GT10
time period	5/1/1962-9/5/2000	10/20/1963-9/5/2000
number of events **(C0;C1;C2;C3;C4)** **(D1;D2;D3;D4)**	246 (32;4;11;13;186) (145;31;21;49)	340 (34;4;14;17;271) (192;47;29;72)
median mislocation (km)	from 12.1 to 11.9	from 12.7 to 13.4
20,40,60,80 percentiles without and with SSSCs (km)	6;11;16;27 6;10;14;22	7;11;17;29 7;11;15;24
% of events improved on GT distance **median improvement**	58% 4.9 km	54% 5.5 km
% of events deteriorated on GT distance **median deterioration**	42% 3.8 km	46% 5.1
% of events improved on GT distance by more than 20%	42%	38%
% of events deteriorated on GT distance by more than 20%	33%	34%
% of events improved on error ellipses **median improvement (sqkm)**	100% 1650 (from 4800 to 3000)	99% 1710 (from 4270 to 2470)
90% ellipse coverage	from 97% to 96%	from 97% to 96%
TRINITY	from 11% to 18%	from 17% to 26%
% of events improved on origin time error **median improvement**	98% 0.5 s (overall from 2.9 to 2.4)	98% 0.6 s (overall from 2.8 to 2.2)
% of event improved on standard error of observations **median improvement**	61% deteriorated 0.4 (overall from 0.9 to 1.1)	58% deteriorated 0.2 (overall from 1.0 to 1.1)

Table 7: Evaluation metrics for relocation of all GT0-GT10 events using Pn and Sn SSSCs for IMS stations only and for IMS+surrogates, along with Pg, and Lg phases (Section 6.3).

	IMS only	**IMS+surrogates**
GT category	GT0-GT10	GT0-GT10
time period	5/1/1962-9/5/2000	5/1/1962-9/5/2000
number of events **(C0;C1;C2;C3;C4)** **(D1;D2;D3;D4)**	261 (32;0;12;11;206) (122;28;29;82)	287 (31;0;14;18;224) (140;44;33;70)
median mislocation (km)	from 14.4 to 15.4	from 13.6 to 14.3
20,40,60,80 percentiles without and with SSSCs	7;11;19;34 6;13;19;32	6;11;17;30 7;11;17;28
% of events improved on GT distance **median improvement**	56% 6.1 km	48% 6.7 km
% of events deteriorated on GT distance **median deterioration**	44% 8.4 km	52% 5.0 km
% of events improved on GT distance by more than 20%	37%	35%
% of events deteriorated on GT distance by more than 20%	36%	39%
% of events improved on error ellipses **median improvement (sqkm)**	99% 1900 (from 6300 to 3950)	99% 1625 (from 5040 to 3100
90% ellipse coverage	from 98% to 97%	from 98% to 97%
TRINITY	from 0% to 3%	from 0% to 4%
% of events improved on origin time error **median improvement**	97% 0.8 (overall from 4.3 to 3.6)	97% 0.7 (overall from 3.6 to 2.7)
% of event improved on standard error of observations **median improvement**	-	-

Table 8: Evaluation metrics for relocation of all GT0-GT10 events using Pn and Sn SSSCs for IMS stations only and for IMS+surrogates, along with teleseismics (Section 6.4)

	IMS only	**IMS+surrogates**
GT category	GT0-GT10	GT0-GT10
time period	9/8/1969-9/5/2000	5/1/1962-9/5/2000
number of events **(C0;C1;C2;C3;C4)** **(D1;D2;D3;D4)**	243 (30;0;18;5;189) (108;50;33;52)	326 (32;3;15;10;266) (157;47;36;86)
median mislocation (km)	from 15.2 to 13.6	from 15.0 to 14.6
20,40,60,80 percentiles without and with SSSCs	7;13;19;35 6;12;17;27	8;13;18;33 7;12;17;30
% of events improved on GT distance **median improvement**	63% 6.8 km	58% 5.4 km
% of events deteriorated on GT distance **median deterioration**	37% 9.0 km	42% 7.3 km
% of events improved on GT distance by more than 20%	50%	42%
% of events deteriorated on GT distance by more than 20%	30%	44%
% of events improved on error ellipses **median improvement (sqkm)**	99% 3090 (from 8880 to 5250)	99% 2310 (from 5860 to 1730)
90% ellipse coverage	from 97% to 96%	from 99% to 98%
TRINITY	from 0% to 3%	from 0% to 5%
% of events improved on origin time error **median improvement**	97% 0.8 s (overall from 4.2 to 3.5)	97% 0.7 s (overall from 3.3 to 2.7)
% of event improved on standard error of observations **median improvement**	-	-

Table 9: Evaluation metrics for relocation of all GT0-GT10 events using Pn and Sn SSSCs for IMS stations only and for IMS+surrogates, with Pg, Lg, and teleseismics (Section 6.5)

	IMS only	IMS+surrogates
GT category	GT0-GT10	GT0-GT10
time period	9/8/1969-9/5/2000	5/1/1962-9/5/2000
number of events **(C0;C1;C2;C3;C4)** **(D1;D2;D3;D4)**	245 (31;0;19;8;186) (126;29;32;58)	328 (32;3;16;12;265) (180;35;34;79)
median mislocation (km)	from 13.4 to 14.2	from 13.0 to 13.1
20,40,60,80 percentiles without and with SSSCs	7;11;16;28 6;11;17;28	7;11;16;25 6;11;16;29
% of events improved on GT distance **median improvement**	60% 5.5 km	50% 5.1 km
% of events deteriorated on GT distance **median deterioration**	40% 8.6 km	50% 5.0 km
% of events improved on GT distance by more than 20%	41%	36%
% of events deteriorated on GT distance by more than 20%	35%	37%
% of events improved on error ellipses **median improvement (sqkm)**	99% 1600 (from 5300 to 3400)	99% 1230 (from 4270 to 2820)
90% ellipse coverage	from 97% to 96%	from 98% to 96%
TRINITY	from 2% to 5%	from 1% to 7%
% of events improved on origin time error **median improvement**	98% 0.7 (from 3.9 to 3.2)	97% 0.6 (from 3.2 to 2.5)
% of event improved on standard error of observations **median improvement**	-	56% deteriorated 0.3 (overall from 1.0 to 1.1)

Table 10: Evaluation metrics for relocation of all GT0-GT10 events using Pn and Sn SSSCs for IMS stations only and for IMS+surrogates, with Pg, Lg, and teleseismics for small events (Section 6.5)

	IMS only tele/reg=1	IMS only tele/reg=3	IMS+surrogates tele/reg=1	IMS+surrogates tele/reg=3
GT category	GT0-GT10	GT0-GT5	GT0-GT10	GT0-GT5
time period	9/8/1969-9/5/2000	9/8/1969-7/29/2000	5/1/1962-9/5/2000	5/1/1962-7/29/2000
number of events (C0;C1;C2;C3;C4) (D1;D2;D3;D4)	30 (13;0;0;0;16) (22;3;0;4)	59 (15;0;8;0;35) (39;8;3;9)	30 (12;0;0;0;16) (23;4;0;3)	85 (14;3;5;0;62) (54;13;0;16)
median mislocation (km)	from 12.6 to 7.6	from 12.9 to 8.0	from 12.1 to 6.3	from 13.7 to 8.2
20,40,60,80 percentiles without and with SSSCs	8;11;14;19 4;6;8;17	7;11;14;20 4;6;9;19	6;12;13;18 4;5;8;12	8;12;16;21 5; 7;12;19
% of events improved on GT distance median improvement	80% 6.1 km	83% 5.5 km	67% 7.0 km	71% 5.0 km
% of events deteriorated on GT distance median deterioration	20% 9.7 km	17% 9.7 km	33% 1.1 km	29% 2.8 km
% of events improved on GT distance by more than 20%	63%	70%	57%	57%
% of events deteriorated on GT distance by more than 20%	17%	12%	13%	18%
% of events improved on error ellipses median improvement (sqkm)	97% 700 (overall from 2250 to 1200)	98% 655 (overall from 2025 to 2340)	100% 630 (from 2190 to 1500)	97% 635 (overall from 2020 to 1510)
90% ellipse coverage	from 97% to 96%		from 90% to 100%	from 95% to 99%
TRINITY	from 10% to 20%	from 7% to 22%	from 7% to 27%	from 4% to 21%
% of events improved on origin time error median improvement	97% 0.3 (from 2.2 to 1.7)	98% 0.3 (from 1.7 to 1.3)	100% 0.3 (from 2.1 to 1.5)	100% 0.3 (from 1.7 to 1.4)
% of event improved on standard error of observations median improvement	-	-	67% deteriorated 0.2 (overall from 1.1 to 1.3)	54% deteriorated 0.2 (overall from 1.2 to 1.3)

Table 11: Evaluation metrics for relocation of Group-2 GT0-GT10 events using regional Pn (and Sn) SSSCs only (Section 7)

	Pn SSSCs only	Pn and Sn SSSCs without maybe S phases	Pn and Sn SSSCs without suspecious Sn	Pn and Sn SSSCs without large residuals
GT category	GT0-GT10	GT0-GT10	GT0-GT10	GT0-GT10
time period	5/1/1962-9/5/ 2000	5/1/1962-9/5/ 2000	5/1/1962-9/5/ 2000	5/1/1962-9/5/ 2000
number of events (C1;C2;C3;C4) (D1;D2;D3;D4)	546	571	571	571
median mislocation(km)	from17.1 to 14.9	from 16.8 to 14.0	from15.9 to14.1	from 16.1 to 13.4
20,40,60,80 percentiles without and with SSSCs (km)	8;13;23;57 7;12;18;34	8;13;22;45 6;11;17;28	7;12;20;41 7;11;17;30	8;13;22;43 6;10;16;28
% of events improved on GT distance (C1;C4) median improvement (C1;C2;C4)	61% 8.3 km	62% 8.0 km	57% 7.9 km	61% 8.0 km
% of events deteriorated on GT distance (C1;C4) median deterioration (C1;C3;C4)	39% 6.3 km	38% 6.1 km	43% 6.6 km	39% 6.2 km
% of events improved on GT distance by more than 20% (C1;C2;C4)	49%	49%	45%	49%
% of events deteriorated on GT distance by more than 20% (C1;C3;C4)	32%	29%	35%	30%
% of events improved on error ellipses median improvement (sqkm)	99% 2600 (overall from 5450 to 2820)	100% 2080 (from 4600 to 2250)	100% 2350 (from 4900 to 2470)	100% 2060 (from 4600 to 2240)
90% ellipse coverage	from 97% to 92%	from 98% to 91%	from 98% to 91%	from 97% to 92%
TRINITY	from 12% to 24%	from 12% to 25%	from 12% to 24%	from 12% to 25%
% of events improved on origin time error median improvement	97% 0.8 s (from 3.2 to2.3)	99% 0.8 (from 3.1 to 2.2)	99% 0.8 (from 3.2 to 2.3)	99% 0.8 (from 3.1 to 2.2)
% of event improved on standard error of observations median improvement	67% 0.2 (overall from 0.9 to 0.8)	63% 0.2 (overall from 1.2 to 1.0)	63% 0.2 (overall from 1.1 to 1.0)	66% 0.2 (from 1.2 to 1.0)

Table 12: Evaluation metrics for relocation of Group-2 GT0-GT10 events using regional Pn and Sn SSSCs for subsets of events (Section 7)

	Pn and Sn SSSCs (no fenno events)	Pn and Sn SSSCs (no explosions)	Pn and Sn SSSCs (no HDC events)
GT category	GT0-GT10	GT0-GT10	GT0-GT10
time period	5/1/1962-9/5/2000	5/1/1962-9/5/2000	5/1/1962-9/5/2000
number of events (C1;C2;C3;C4) (D1;D2;D3;D4)	403	464	379
median mislocation(km)	from17.8 to 14.1	from 13.1 to 11.9	from15.4 to 14.1
20,40,60,80 percentiles without and with SSSCs (km)	9;14;24;49 6;11;17;32	7;11;17;29 6;10;15;26	7;12;21;45 6;11;17;29
% of events improved on GT distance (C1;C4) median improvement (C1;C2;C4)	65% 8.9 km	59% 6.0 km	59% 7.6 km
% of events deteriorated on GT distance (C1;C4) median deterioration (C1;C3;C4)	35% 7.1 km	41% 5.8 km	41% 6.3 km
% of events improved on GT distance by more than 20% (C1;C2;C4)	53%	46%	46%
% of events deteriorated on GT distance by more than 20% (C1;C3;C4)	28%	32%	31%
% of events improved on error ellipses median improvement (sqkm)	100% 1520 (from 2890 to 1320)	99% 1875 (from 3880 to 22519200)	100% 2525 (from 5730 to 3070)
90% ellipse coverage	from 97% to 92%	from 98% to 91%	from 98% to 91%
TRINITY	from 17% to 35%	from 15% to 29%	from 8% to 16%
% of events improved on origin time error median improvement	99% 0.7 s (from 2.5 to 1.7)	99% 0.7 (from 2.2 to 2.0)	99% 0.8 (from 4.0 to 3.0)
% of event improved on standard error of observations median improvement	66% 0.2 (overall from 1.5 to 1.3)	65% 0.2 (overall from 1.1 to 0.9)	-

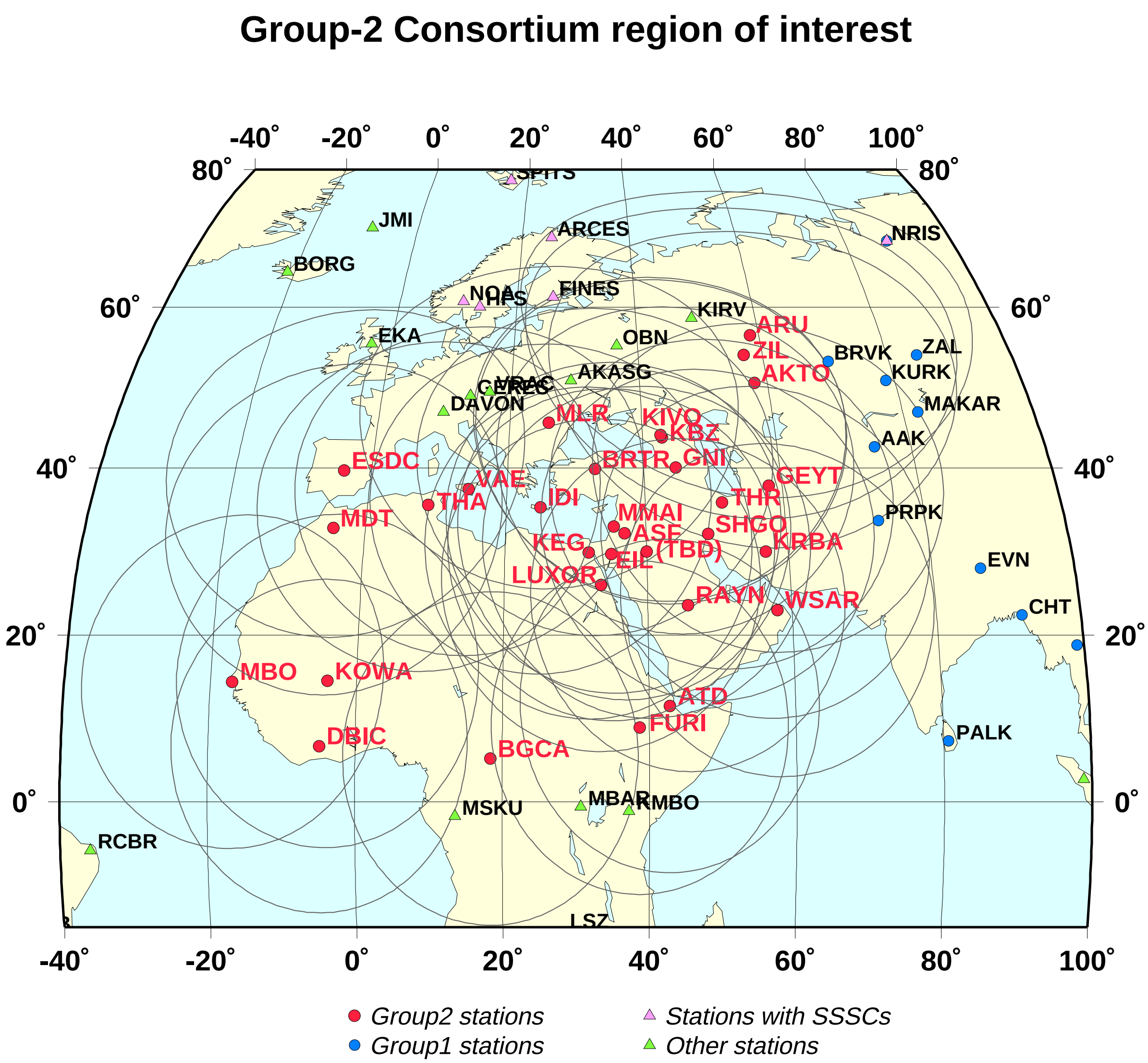


Figure 1. Group-2 consortium region of interest, including 32 IMS primary and auxiliary Group-2 stations. There are six IMS stations with existing SSSCs based on a 1D approach (Yang and McLaughlin, 1999).

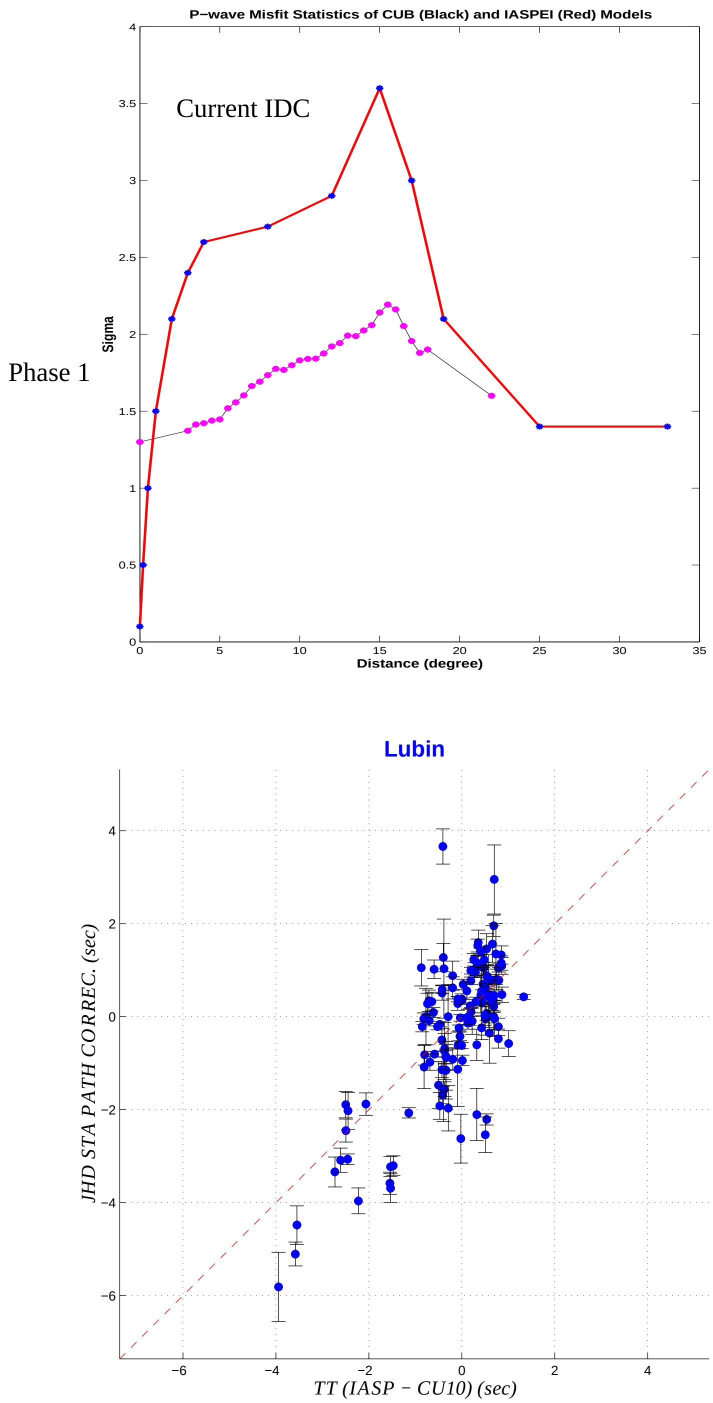


Figure 2.(Top) Modeling errors used in Phase 1 (thin line) compared to that used at the PIDC/IDC currently (thick line). (Bottom) Empirical path correction comparisons of the Lubin, Poland, cluster and the CUB model. There is good agreement between the empirical JHD path corrections and the model predictions (correlation coefficient of 0.8).

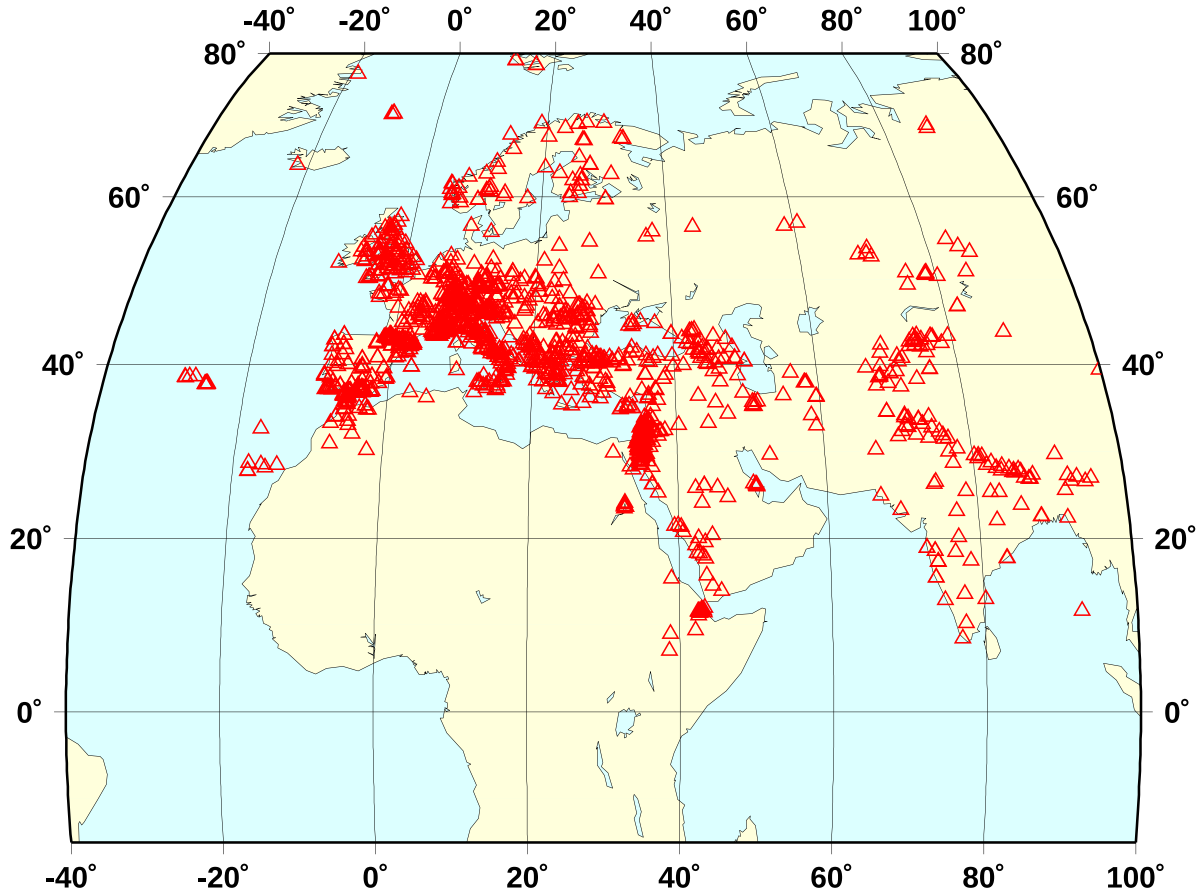


Figure 3. About 1300 stations in the study region that are used in validation testing with Pn and Sn SSSCs.

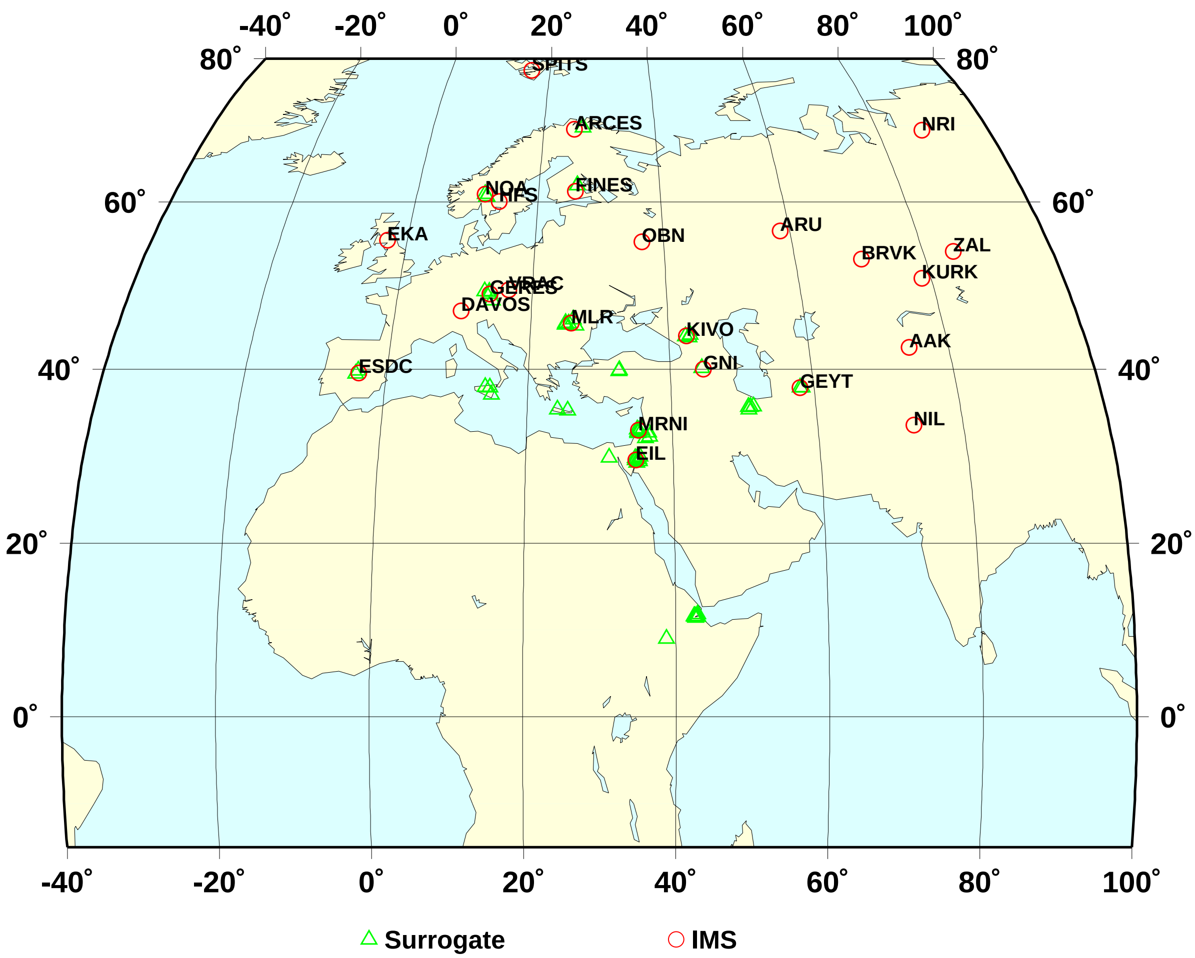


Figure 4. About 85 IMS and surrogate stations in the study region that are used in relocation with Pn and Sn SSSCs. They include all Group-2 stations from Israelsson's surrogate station list and non-Group2 stations from Engdahl's surrogate station list. They also include non-Group2 IMS stations for which no surrogate stations are available.

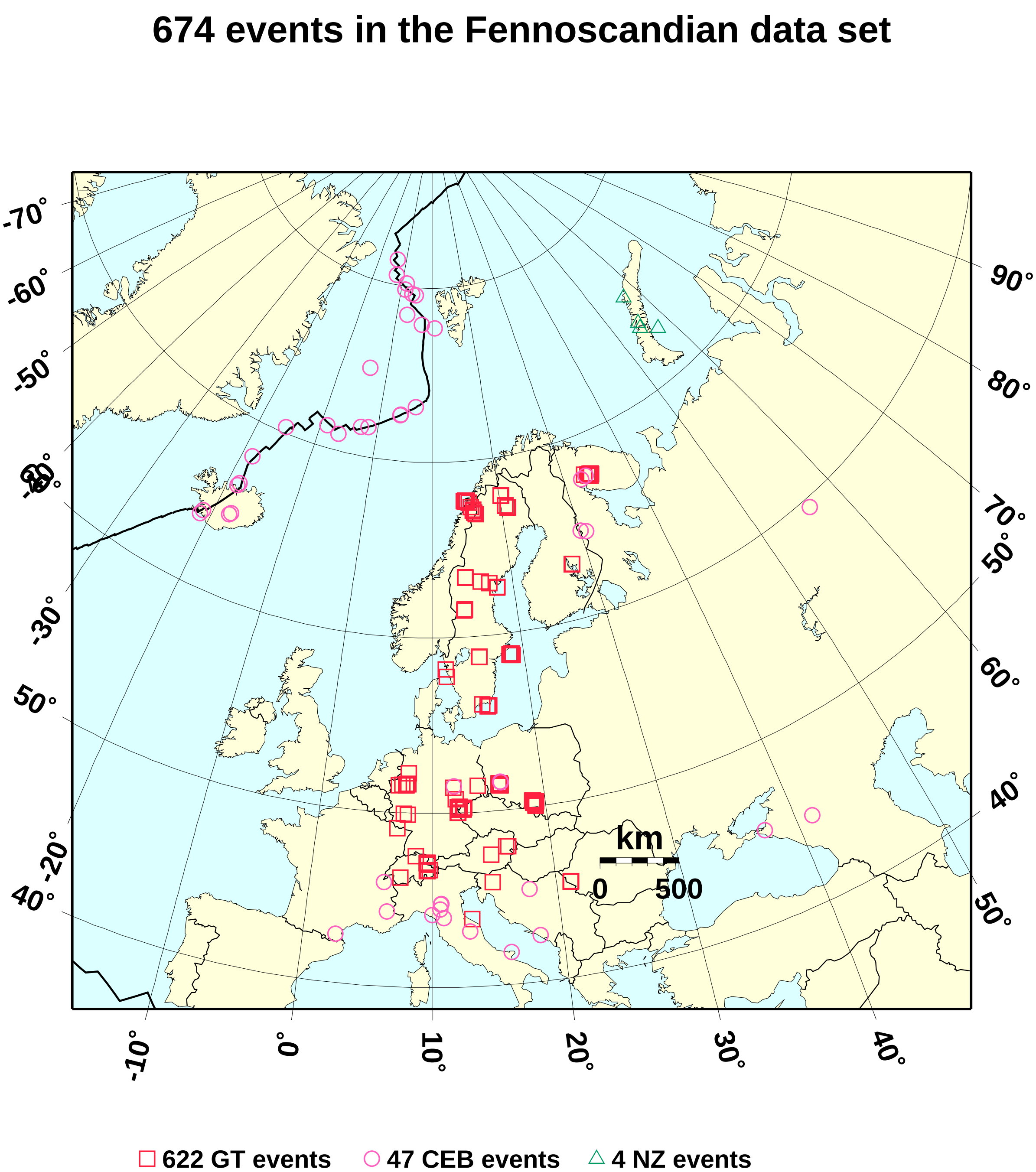


Figure 5. Events in the Fennoscandian data set used in validation testing (Section 4). About 180 events are in the Group-2 GT0-GT10 data set (Figure 6).

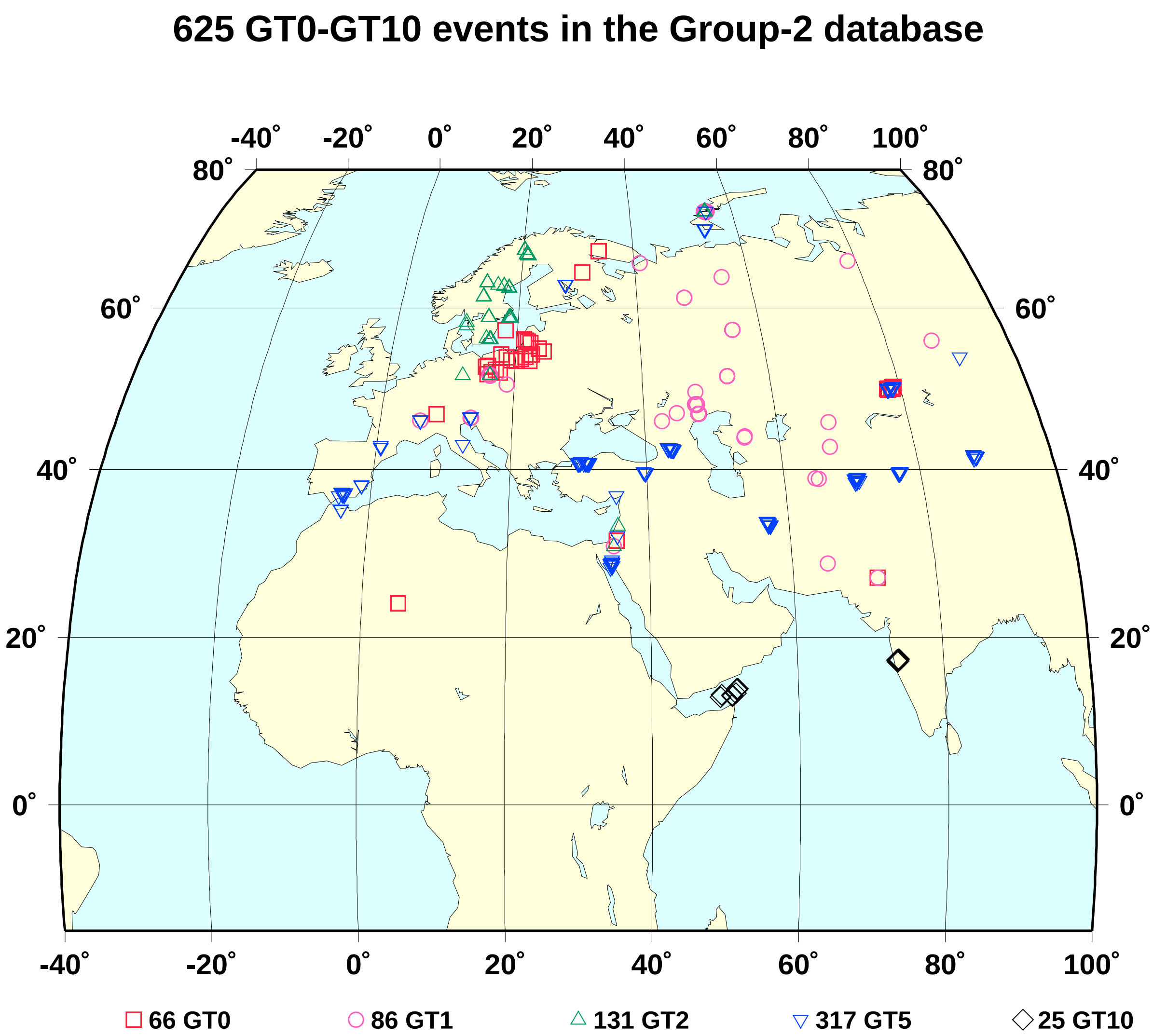


Figure 6. GT0-GT10 events in the Group-2 GT0-GT10 data set that are used in validation testing (Sections 5-6).

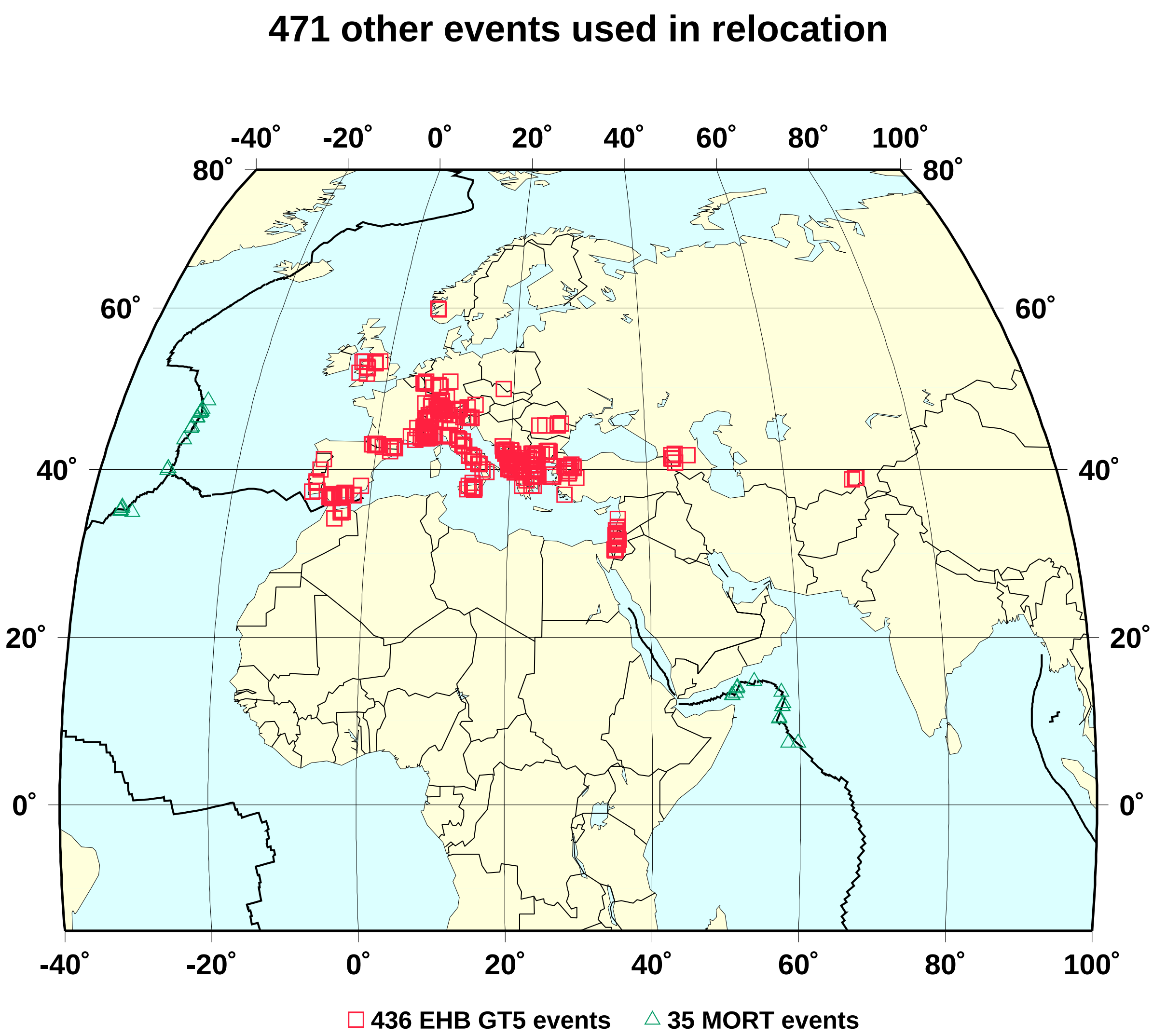


Figure 7. Other events used in relocation, including MORT GT10 events and estimated GT5 EHB events (Section 5).

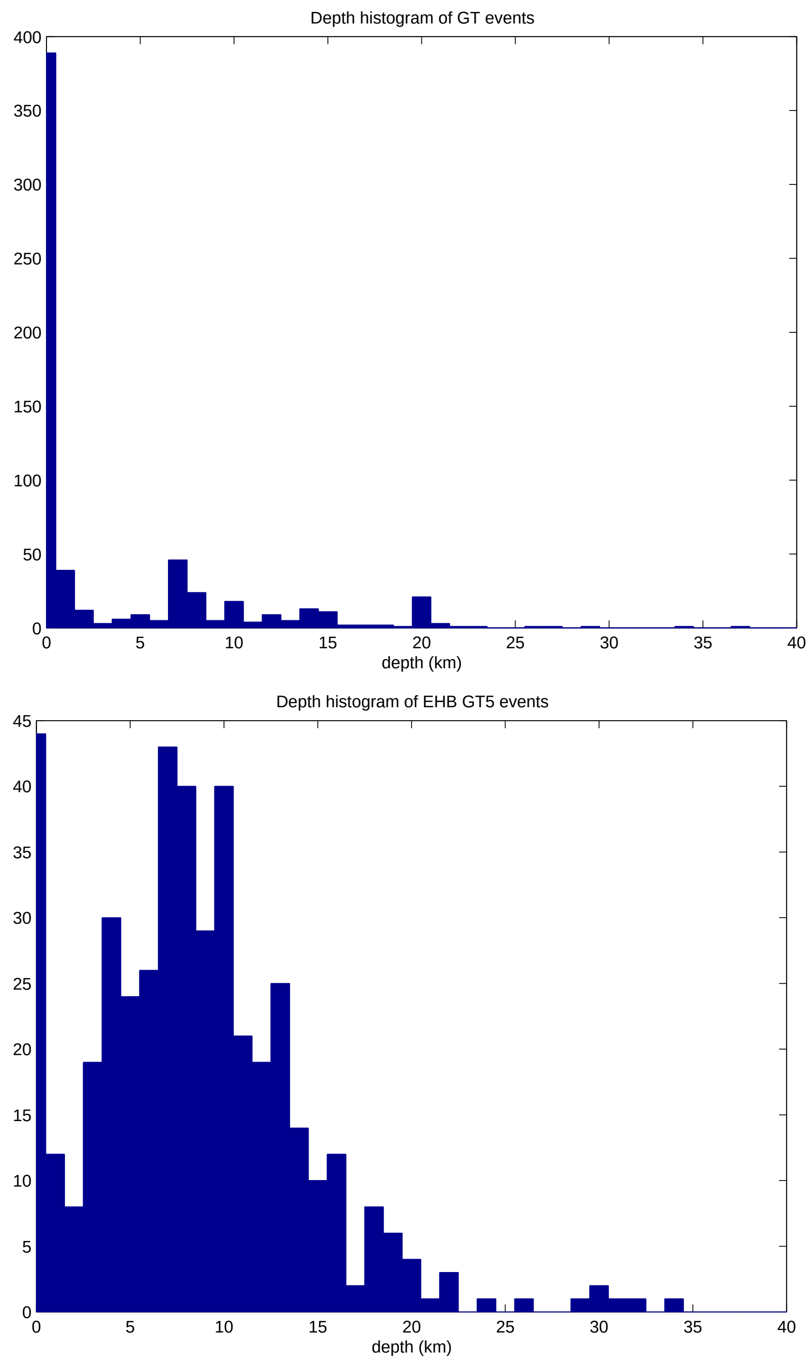


Figure 8. Depths of the events used in validation testing from the Group-2 GT0-GT10 data set and estimated GT5 EHB events (Sections 5-6). (Top) The Group-2 GT0-GT10 events. Most events are less than a few km deep. The median is zero and the mean is 3.6 km. (Bottom) The estimated EHB GT5 events. The median/mean depth is about 8 km.

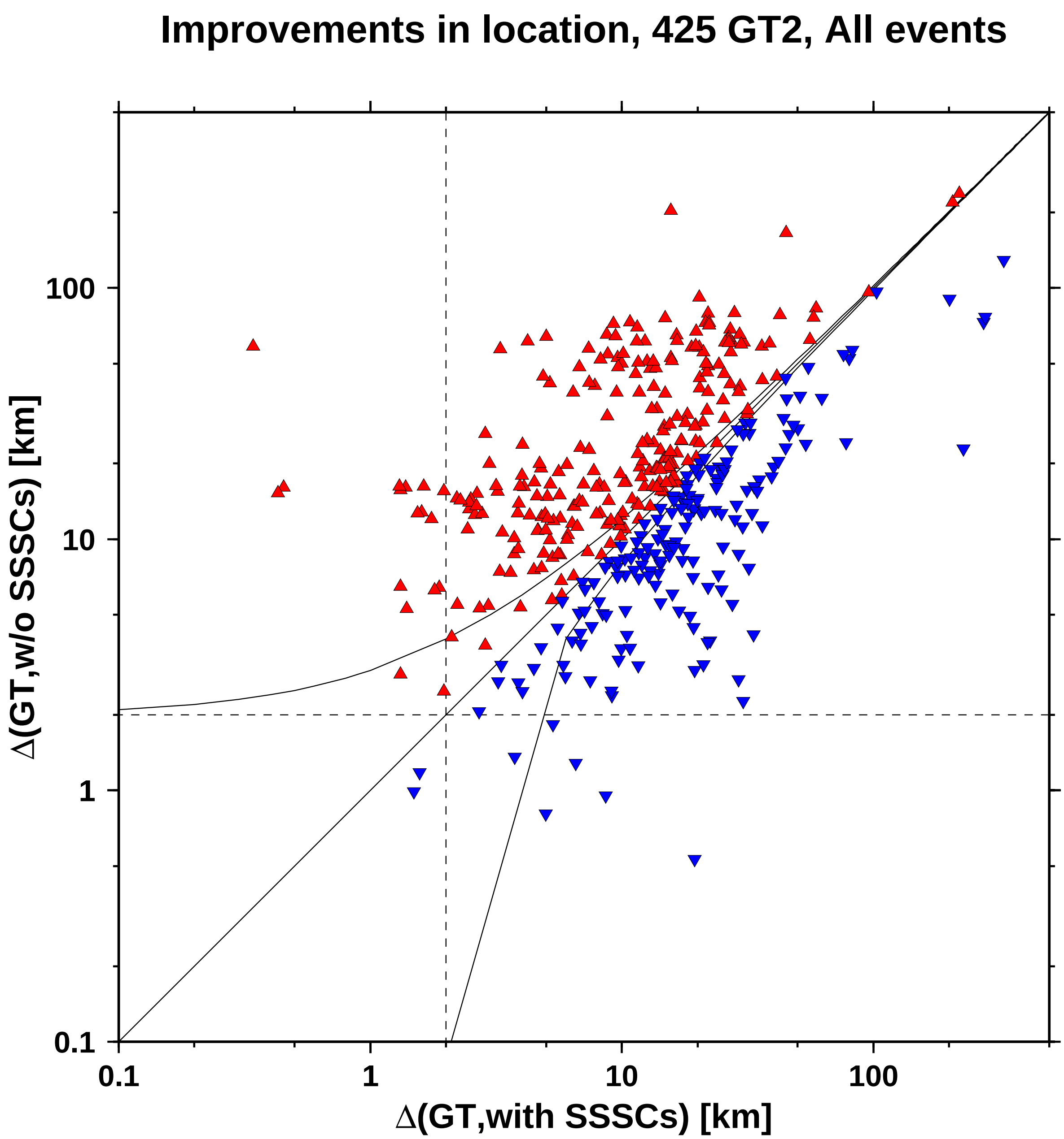


Figure 9. Mislocations for the GT events in the Fennoscandian data set with (red triangles) and without (blue invert triangles) SSSCs (Section 4). These events were considered as GT2 events in Yang and McLaughlin (1999). The 2-km bound (dashed lines) and GT2 uncertainty (curved lines) are plotted. Symbols above the diagonal line indicate improvement with SSSCs.

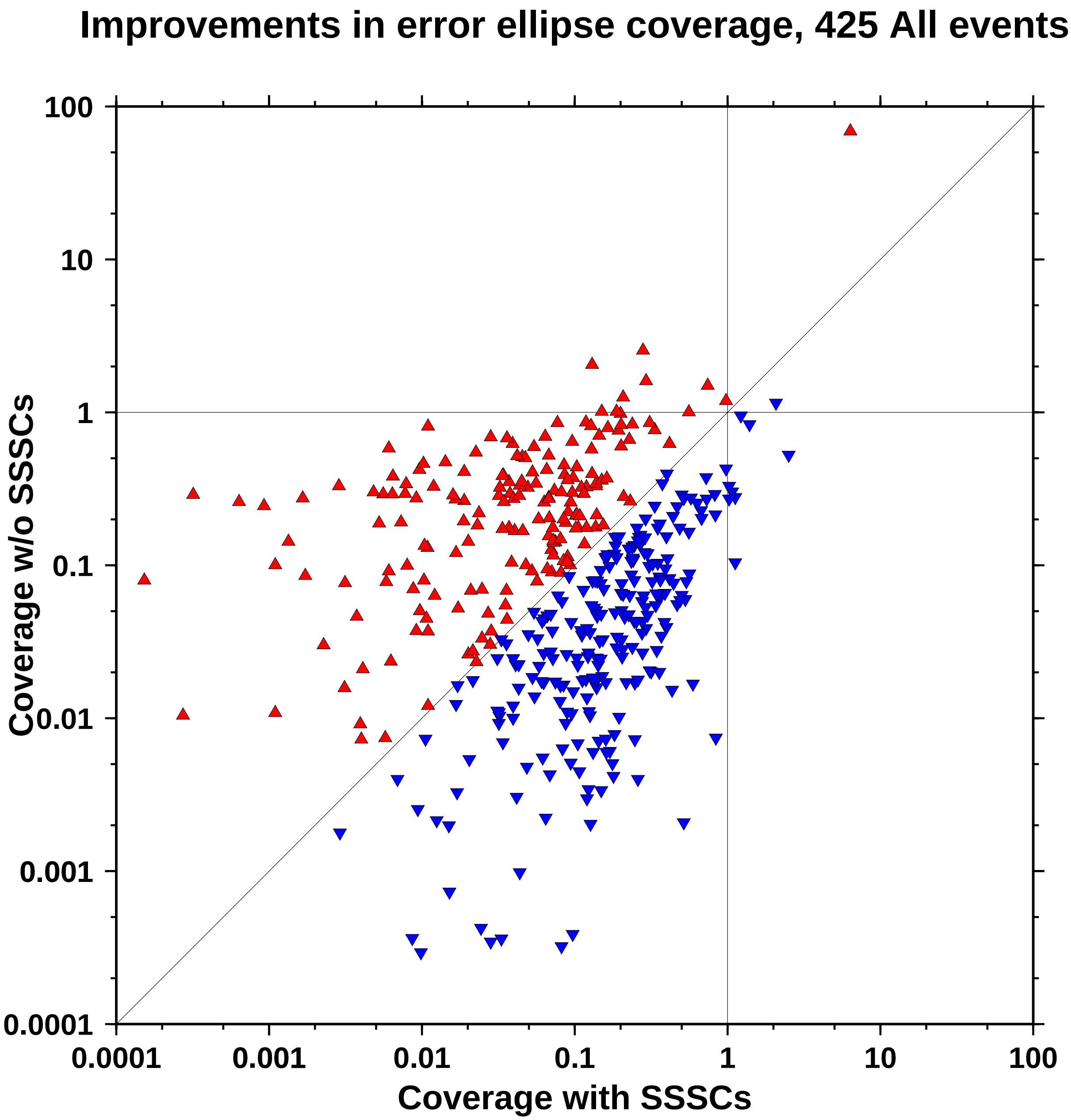


Figure 10. Ellipse coverage for the GT events in the Fennoscandian data set with (red triangles) and without (blue invert triangles) SSSCs (Section 4). The 90% coverages (=1) are plotted for both cases (lines). Symbols above the diagonal line indicate improvement with SSSCs

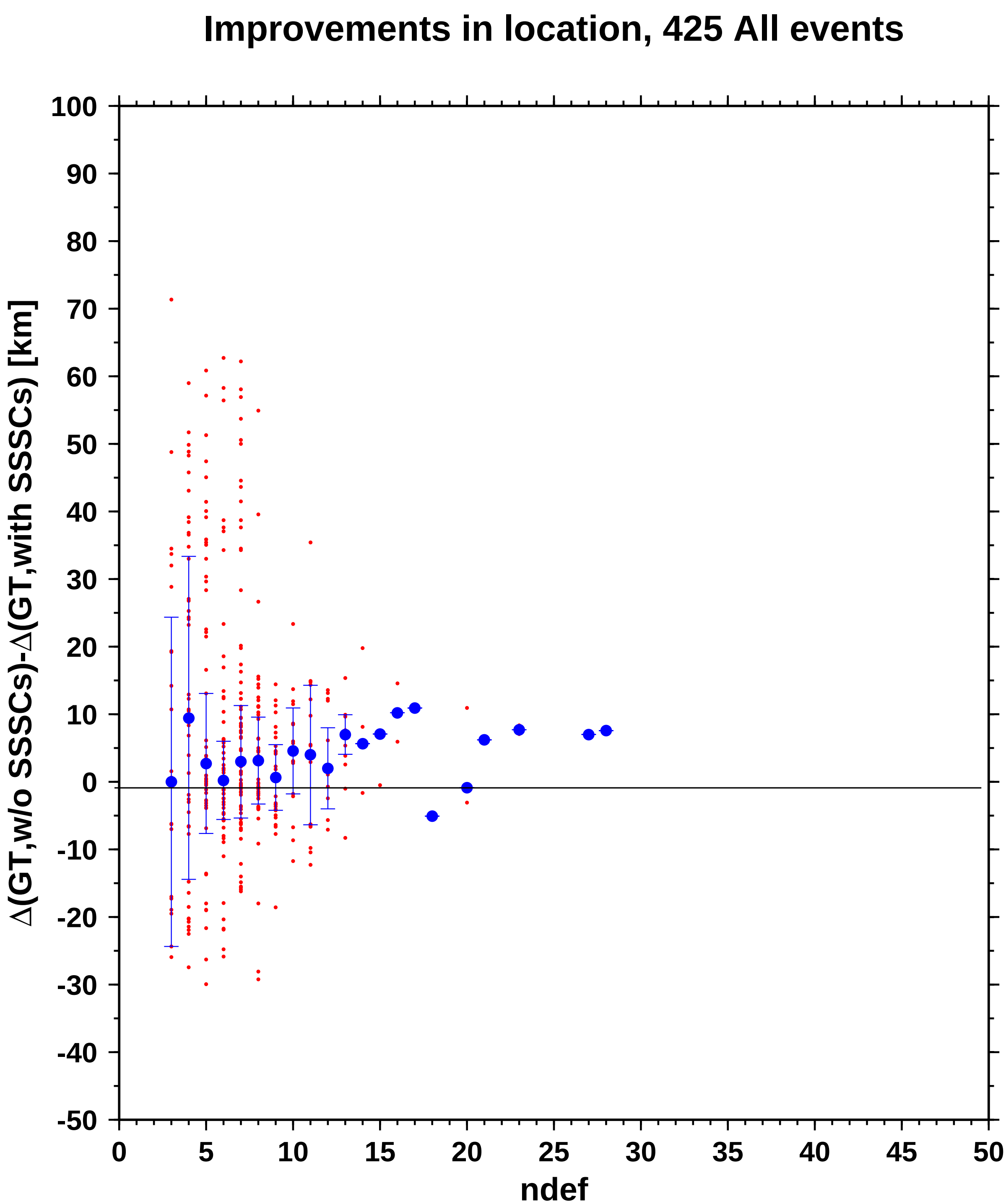


Figure 11. Mislocation vs. ndef for the GT events in the Fennoscandian data set with and without SSSCs (Section 4). The small red dots are mislocation improvements with SSSCs. The large blue dots are the medians of the ndef groups, and the blue bars are the spreads (when more than 10 observations exist). Positive numbers indicate improvement. There are large improvements for low ndef events when SSSCs are applied.

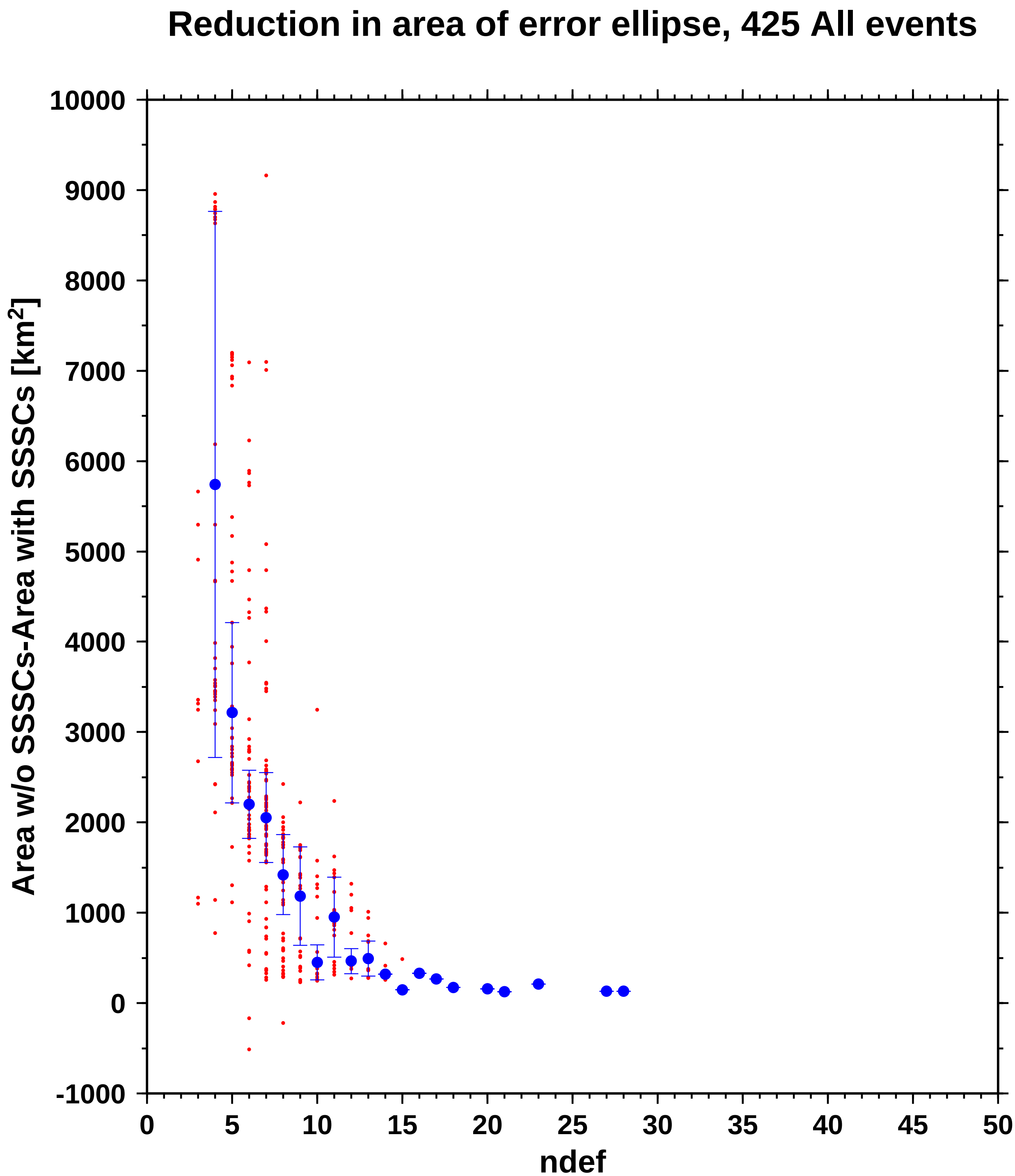


Figure 12. Error ellipse area vs. ndef for the GT events in the Fennoscandian data set with and without SSSCs (Section 4). The small red dots are ellipse area improvements with SSSCs. The large blue dots are the medians of the ndef groups, and the blue bars are the spreads (when more than 10 observations exist). Positive numbers indicate improvement. There are large improvements for low ndef events when SSSCs are applied.

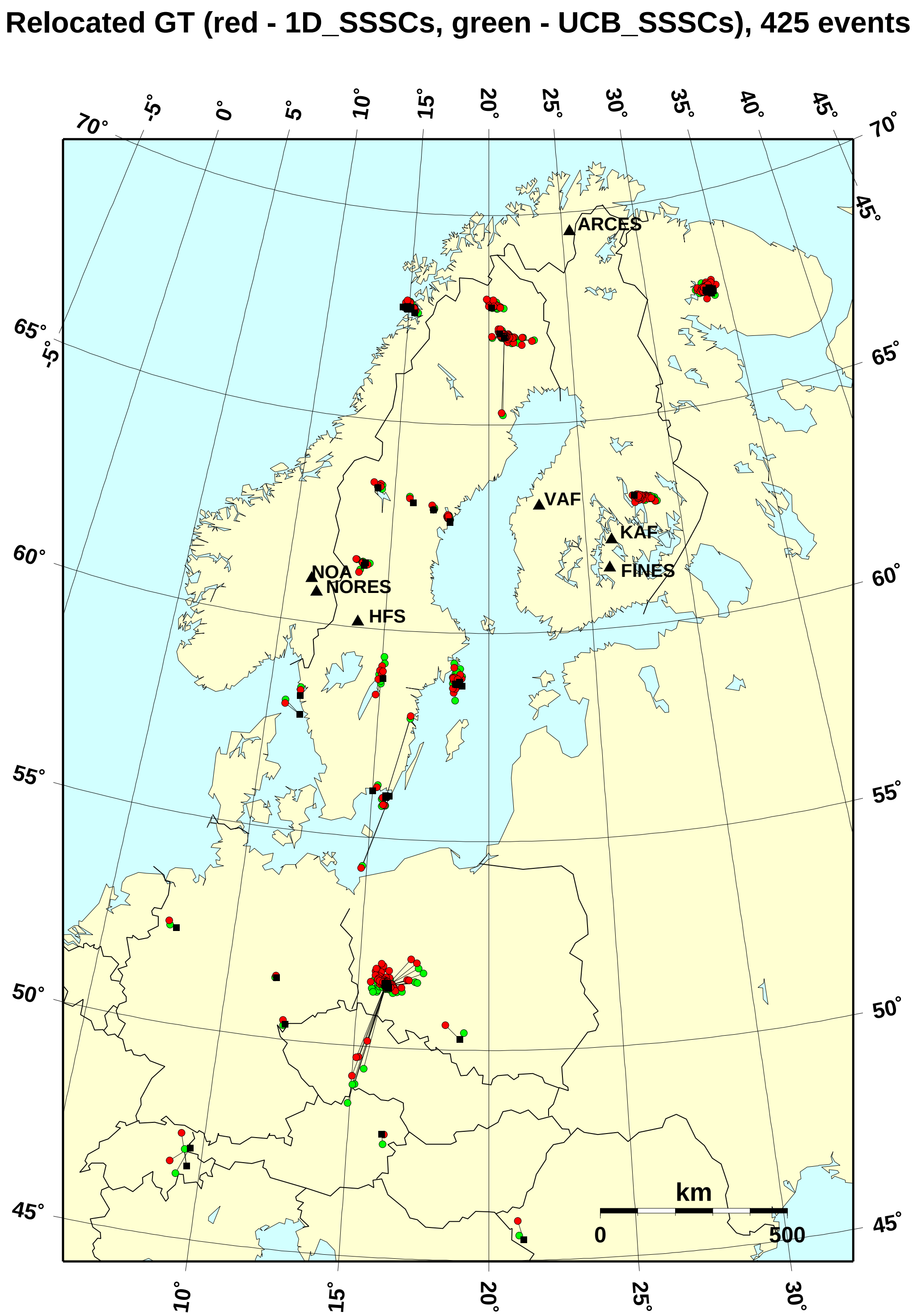


Figure 13. Direct comparisons of relocated events using the 1D and CUB Pn and Sn SSSCs, respectively (Section 4).

Relocated CEB (red - 1D_SSSC, green - UCB_SSSC), 40 events

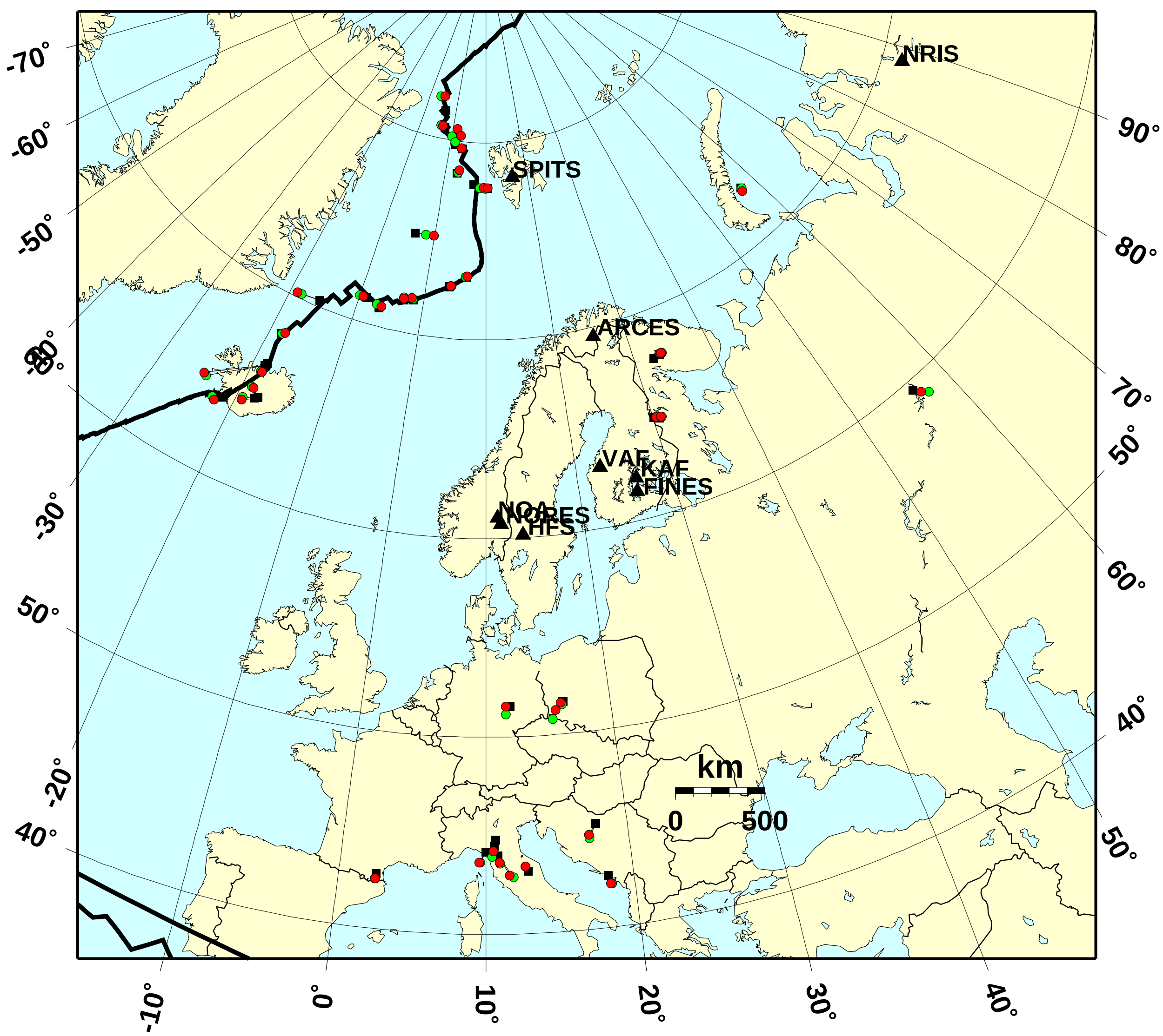


Figure 14. Direct comparisons of relocated CEB events in the Fennoscandian data set using the 1D (red) and CUB (green) Pn and Sn SSSCs, respectively (Section 4). Relocation of the ridge events using both models is consistent with the geological feature.

Event 97/08/16 (red - w/SSSCs, green - w/oSSSCs)

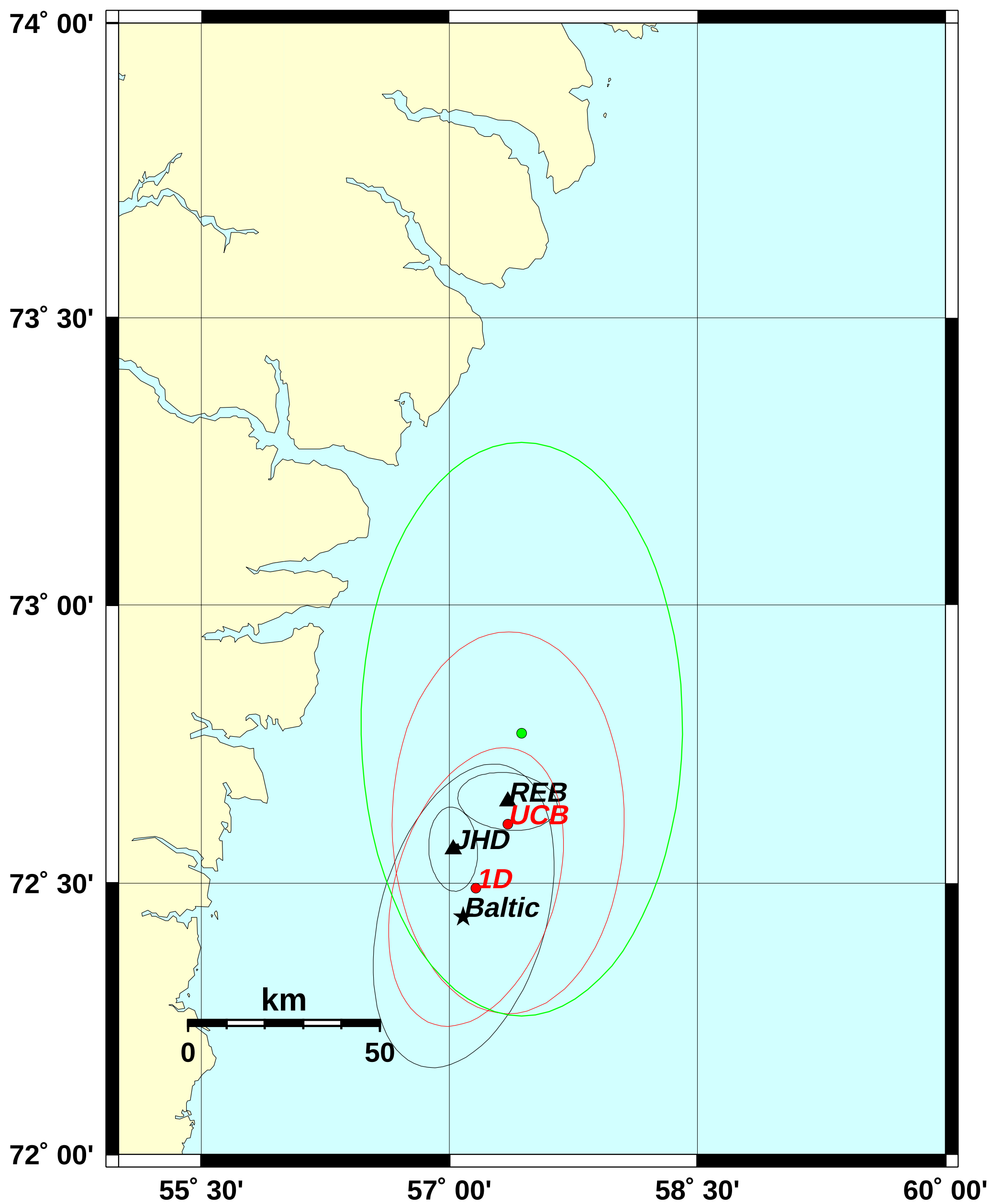


Figure 15. Comparisons of relocated NZ event on 08/16/1997 in the Fennoscandian data set (Section 3) using the 1D (red) and CUB (red) Pn and Sn SSSCs, as well as without SSSCs (green).

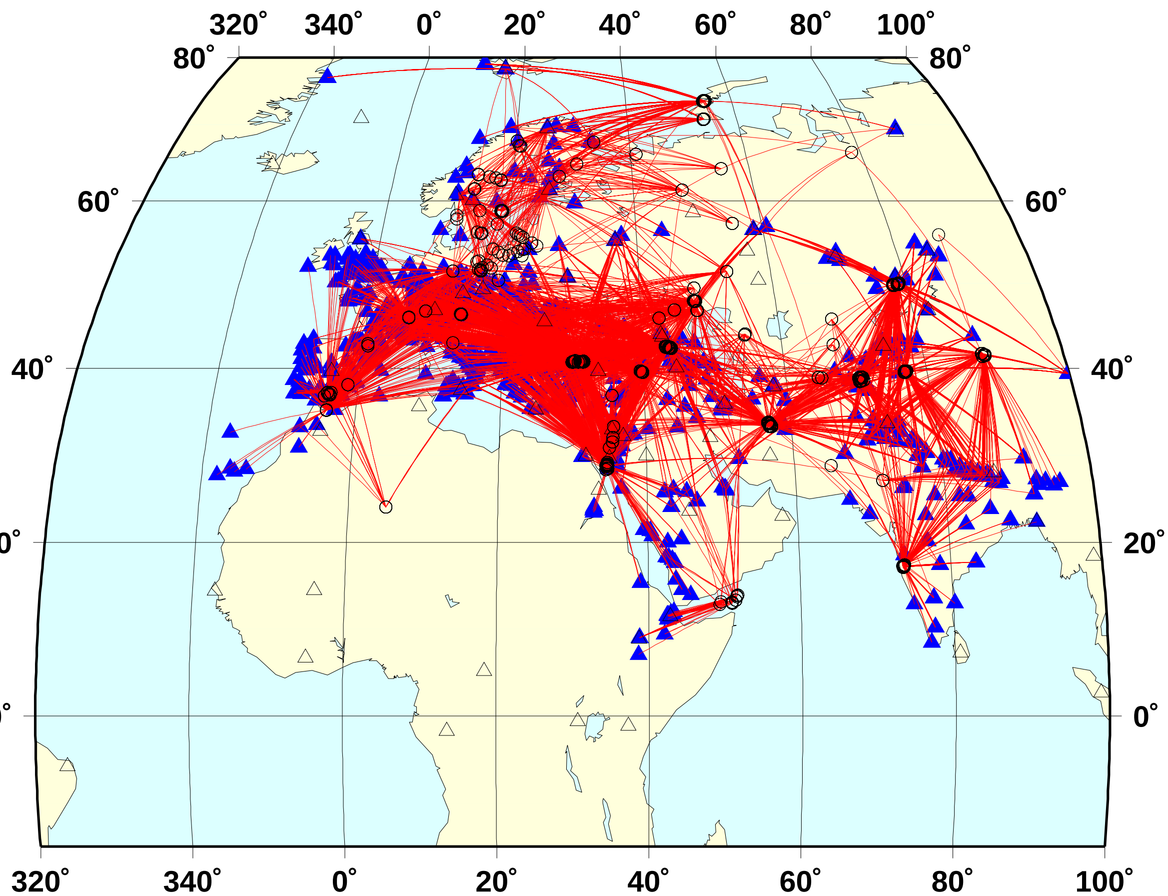


Figure 16a. Over 10,000 regional Pn paths in the Group-2 GT0-GT10 data set. Events (circles) and stations (open triangles for IMS; solid triangles for other stations) are also plotted.

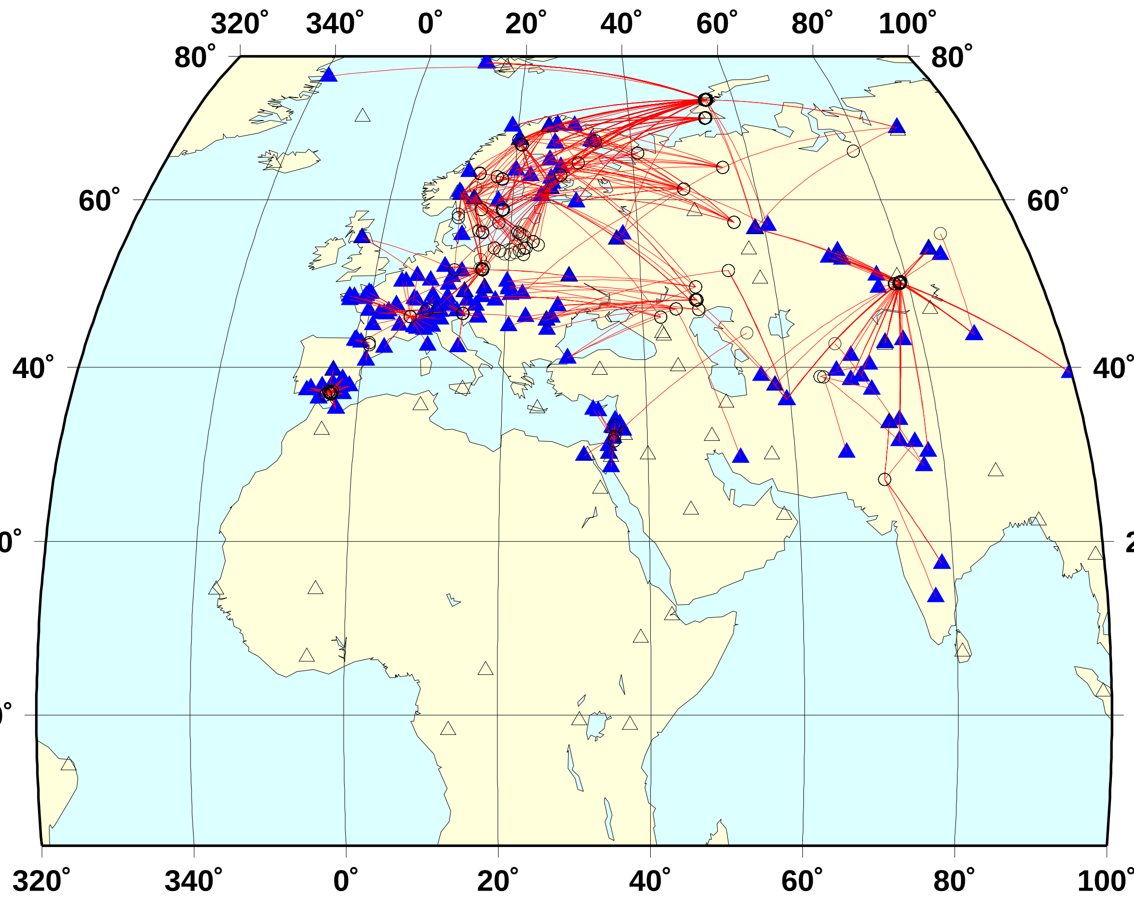


Figure 16b. Over 600 regional Sn paths in the Group-2 GT0-GT10 data set. Events (circles) and stations (open triangles for IMS; solid triangles for other stations) are also plotted.

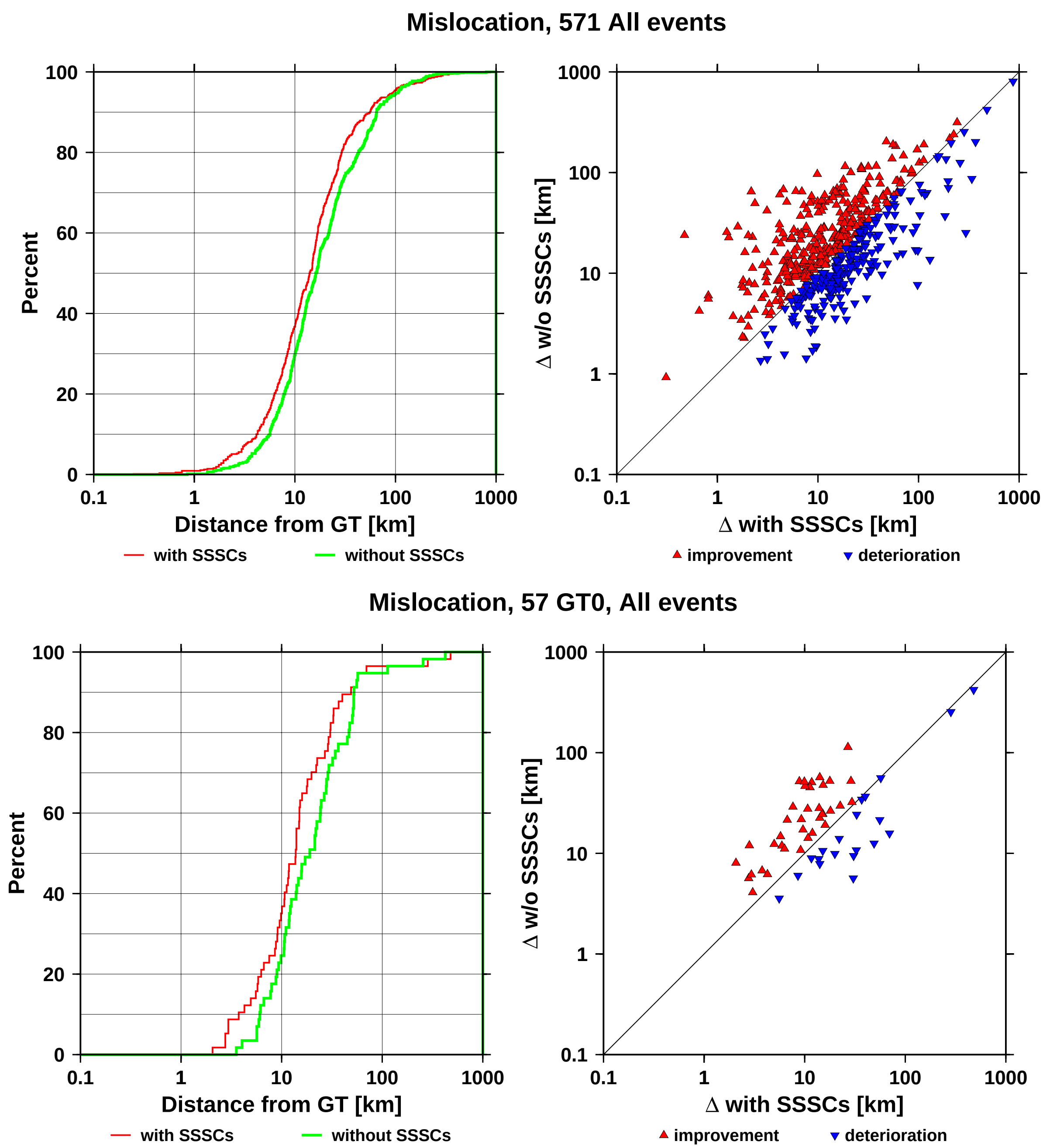


Figure 17a. Mislocations of the GT0-GT10 events with and without SSSCs (Section 5). (Top) All GT0-GT10 events. (Bottom) GT0 events only. They include nuclear explosions in STS, Sahara, India, and Pakistan, calibration shots in Dead Sea, Kazakhstan, and Kola peninsula, seismic experiment Polonaise and Eurobridge, and a chemical explosions in Switzerland. (Left) Cumulative plot of mislocation. (Right) Comparisons of mislocation with (red triangle) and without (blue inverse triangle) SSSCs. Symbols above the diagonal line indicate improvement with SSSCs.

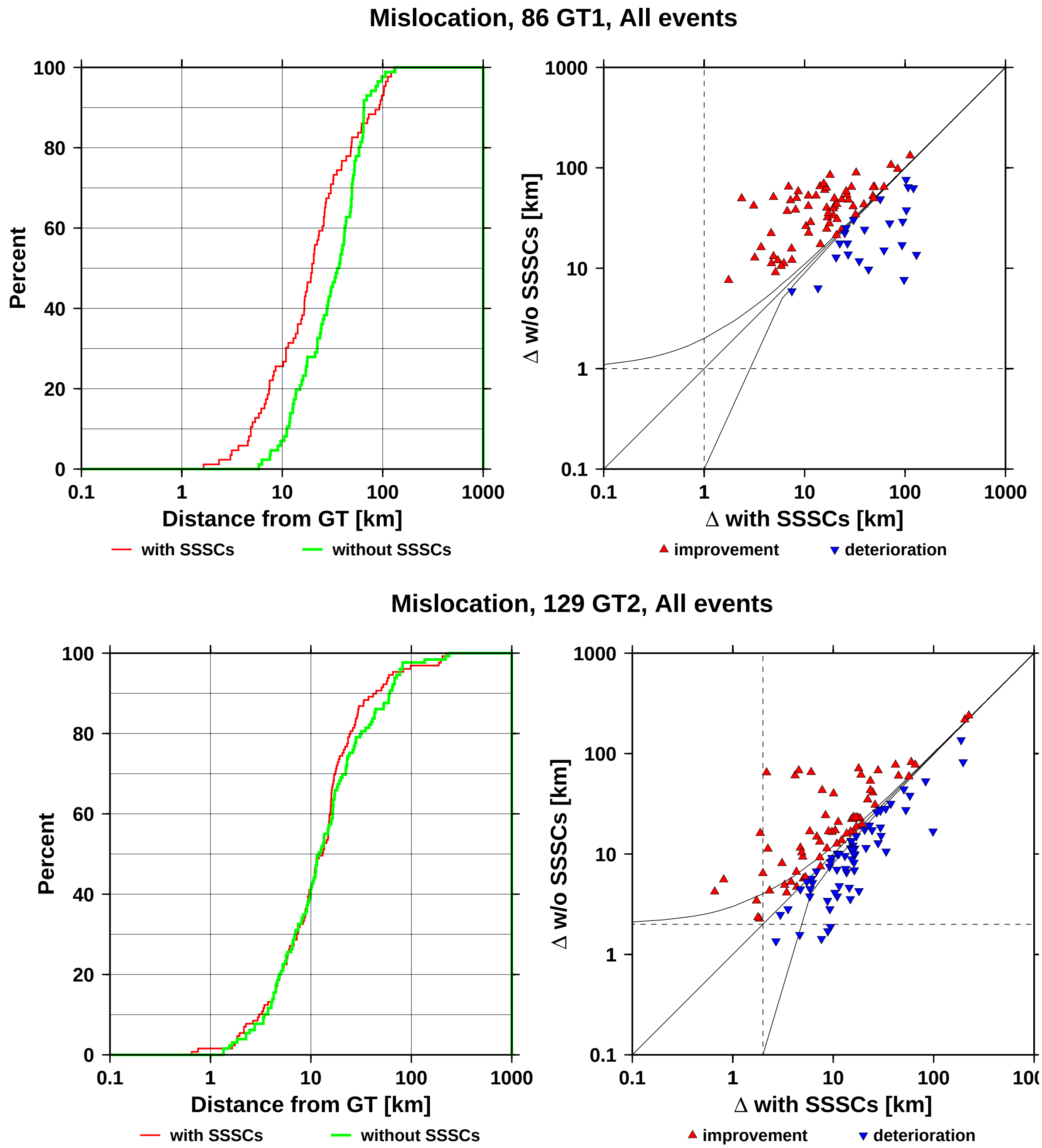


Figure 17b. Mislocations of the GT1 (Top) and GT2 (Bottom) events with and without SSSCs (Section 5). The GT1 events are nuclear explosions in NZ and PNEs, mine tremors in Poland, a quarry blast in Israel, a French earthquake, and an aftershock sequence in Slovenia. The GT2 events are nuclear explosions in NZ, a mine collapse in Germany, mining events in Poland and Fennoscandia. (Left) Cumulative plot of mislocation. (Right) Comparisons of mislocation with (red triangle) and without (blue inverse triangle) SSSCs. The1-km and 2-km bounds (dashed lines) and GT1 and GT2 uncertainties (curved lines) are plotted, respectively. Symbols above the diagonal line indicate improvement with SSSCs.

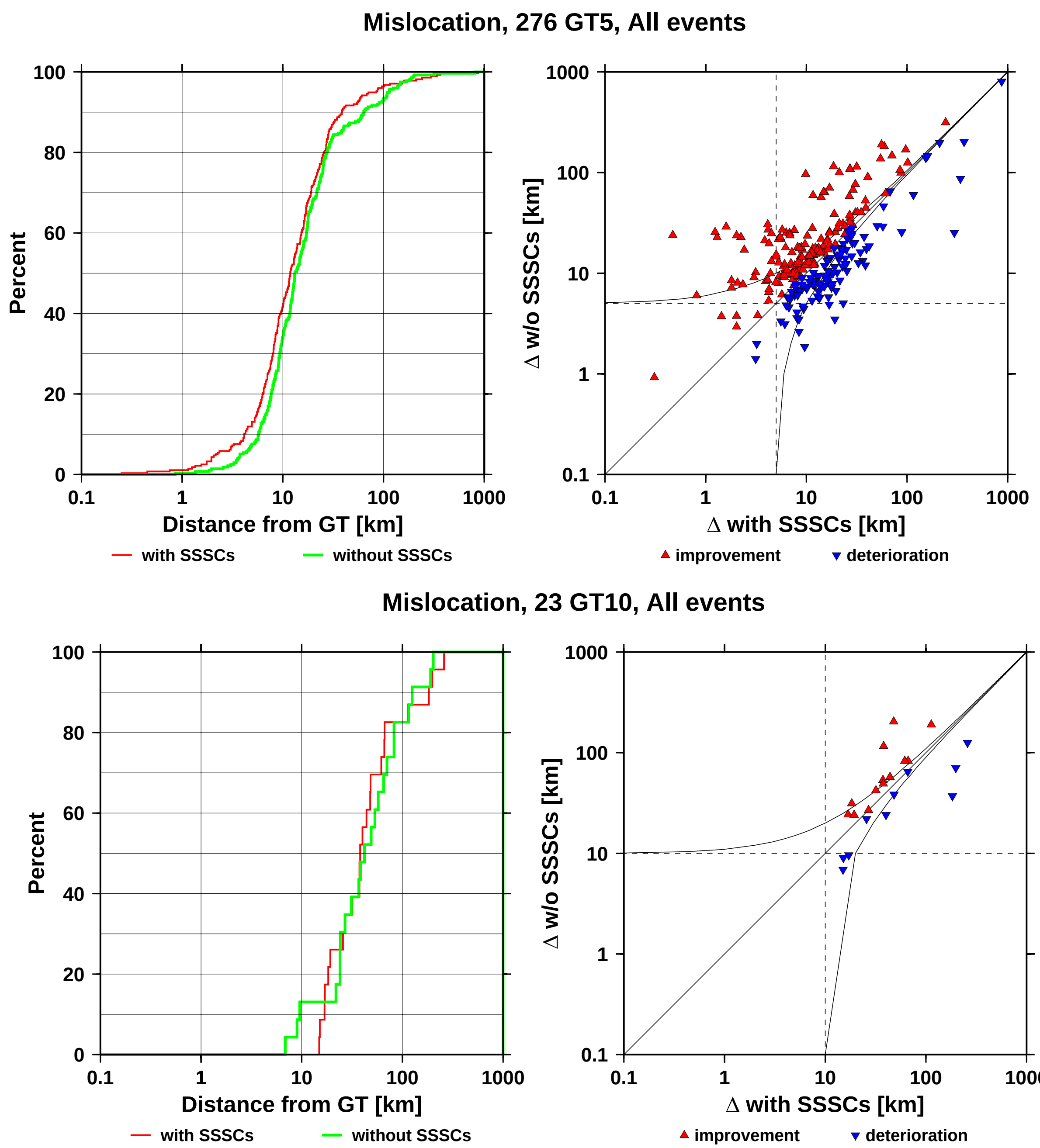


Figure 17c. Mislocations of the GT5 (Top) and GT10 (Bottom) events with and without SSSCs (Section 5). The GT5 events are mostly clusters from the HDC analysis, as well as nuclear explosions in NZ and Lop Nor, mining events in Fennoscandia, earthquakes from the IGN, and in Pyrenees, Israel, and Turkey. The GT10 events are the Aden and Koyna clusters from the HDC analysis. (Left) Cumulative plot of mislocation. (Right) Comparisons of mislocation with (red triangle) and without (blue inverse triangle) SSSCs. The5-km and 10-km bounds (dashed lines) and GT5 and GT10 uncertainties (curved lines) are plotted, respectively. Symbols above the diagonal line indicate improvement with SSSCs.

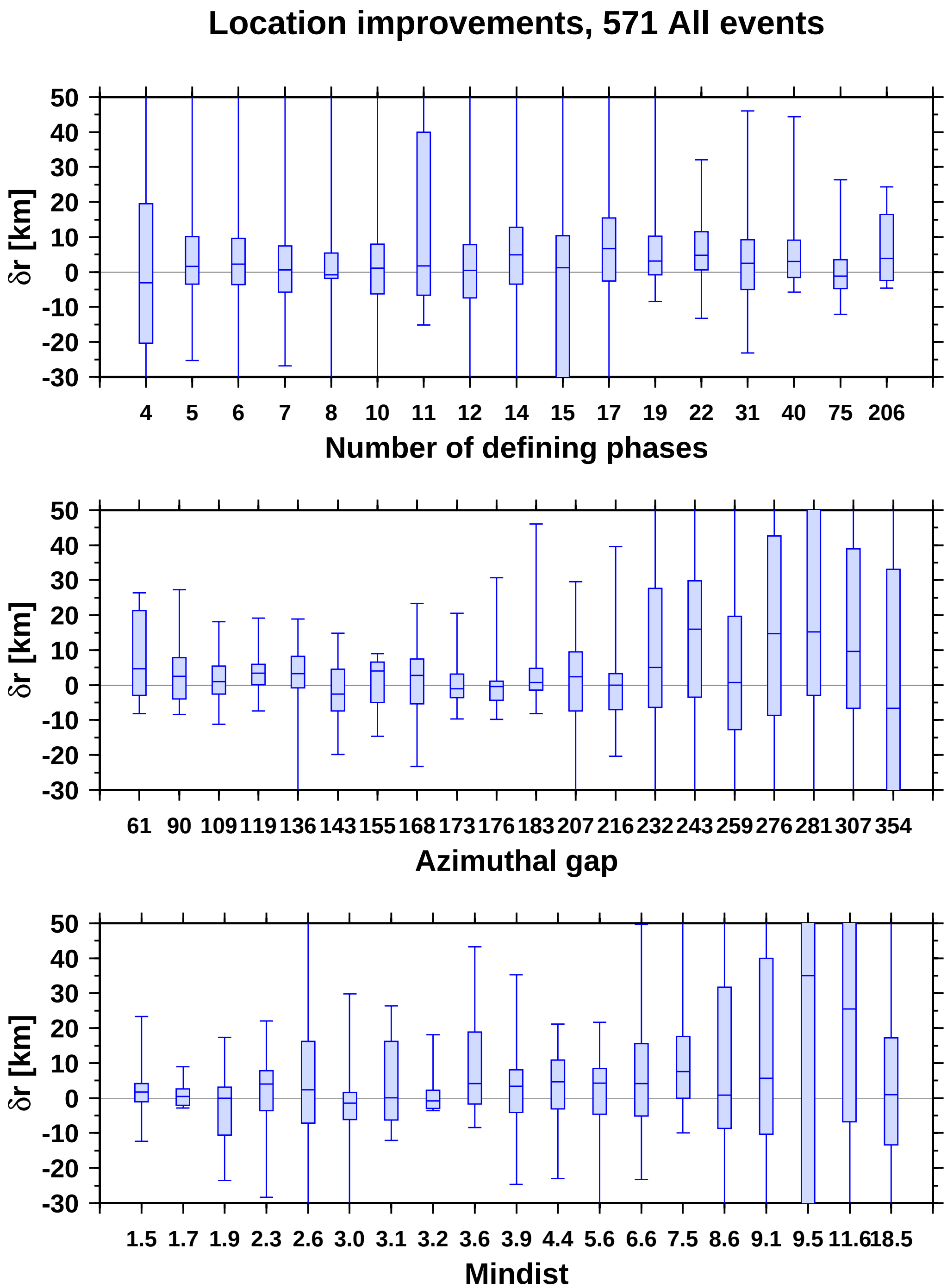


Figure 18a. Location improvements of the GT0-GT10 events with SSSCs versus ndef, azimuthal gap, and minimum distance in degrees (Section 5). In each plot the bins vary according to the cumulative distributions, and only data within the 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

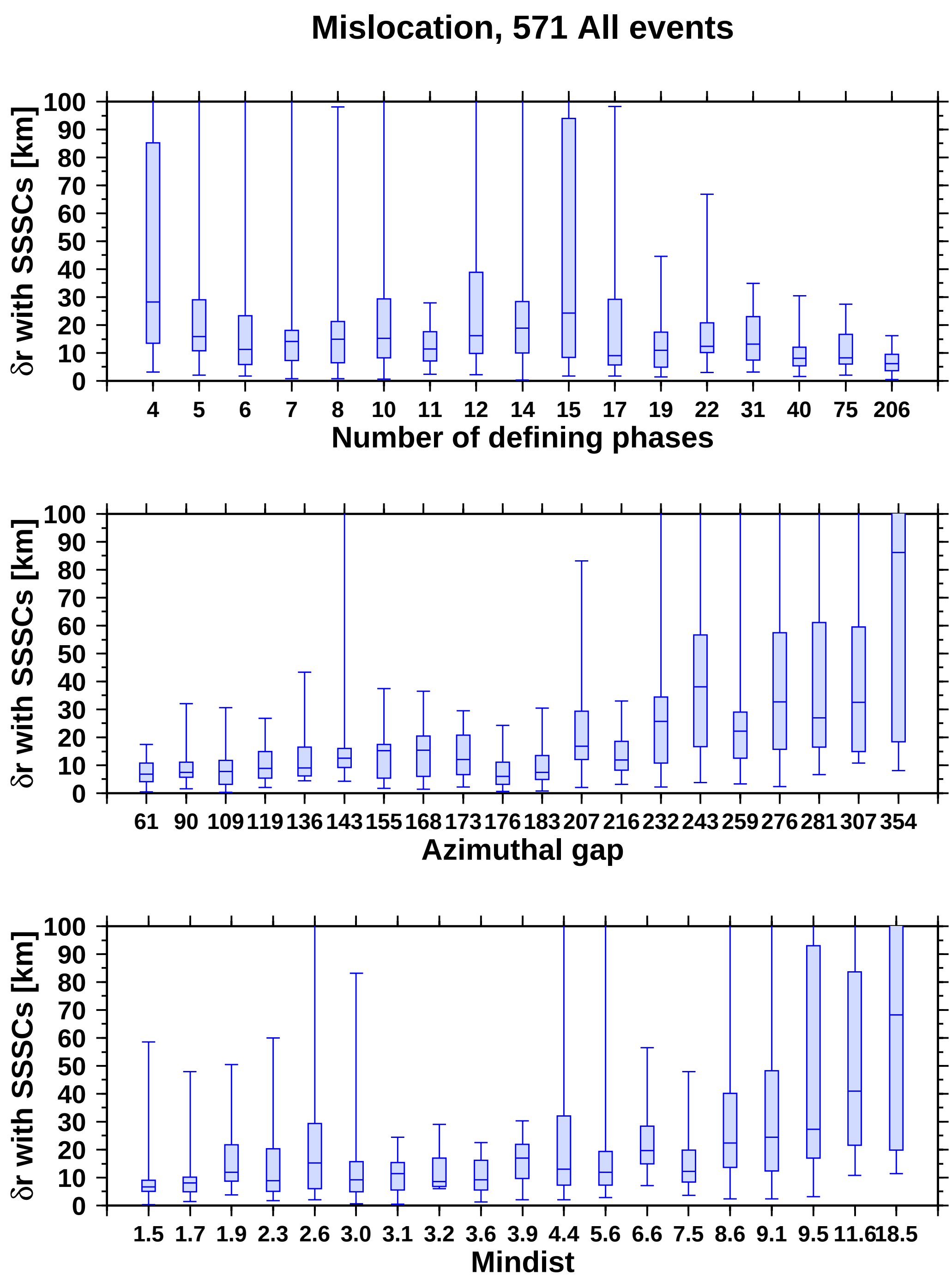


Figure 18b. Mislocations of the GT0-GT10 events with SSSCs versus ndef, azimuthal gap, and minimum distance in degrees (Section 5). In each plot the bins vary according to the cumulative distributions, and only data within the 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

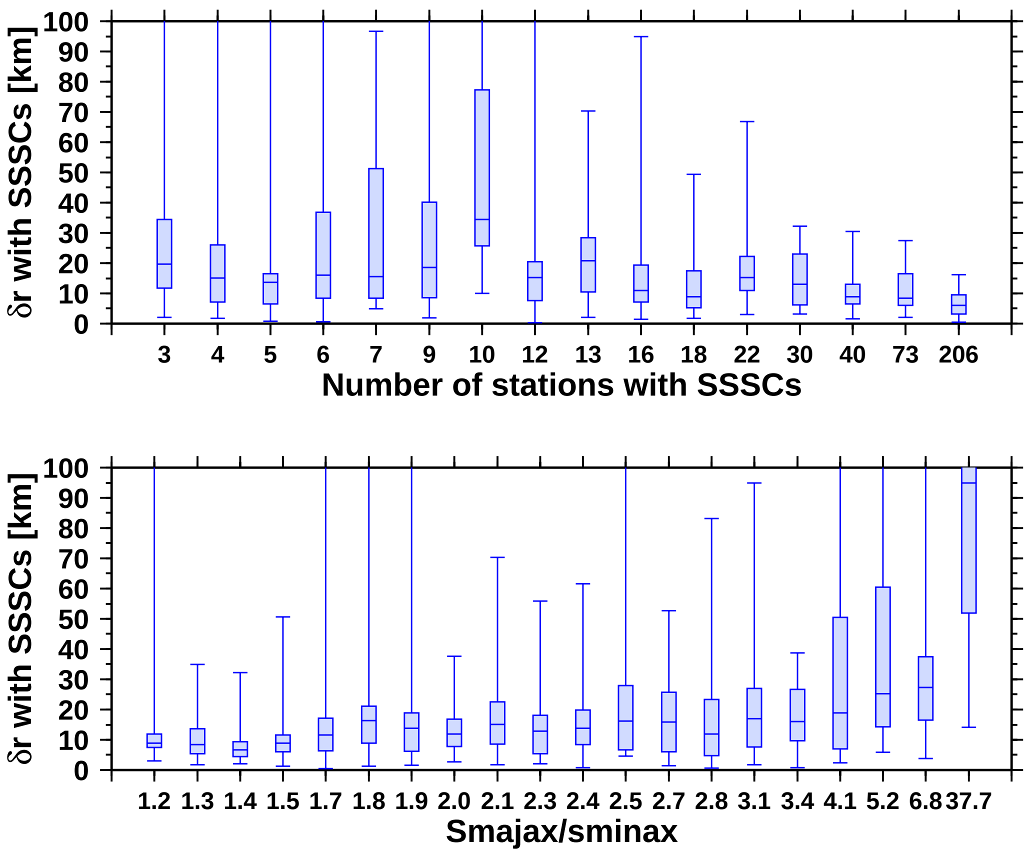


Figure 18c. Mislocations of the GT0-GT10 events with SSSCs versus number of defining stations with SSSCs and error ellipse axis ratio (Section 5). In each plot the bins vary according to the cumulative distributions, and only data within the 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

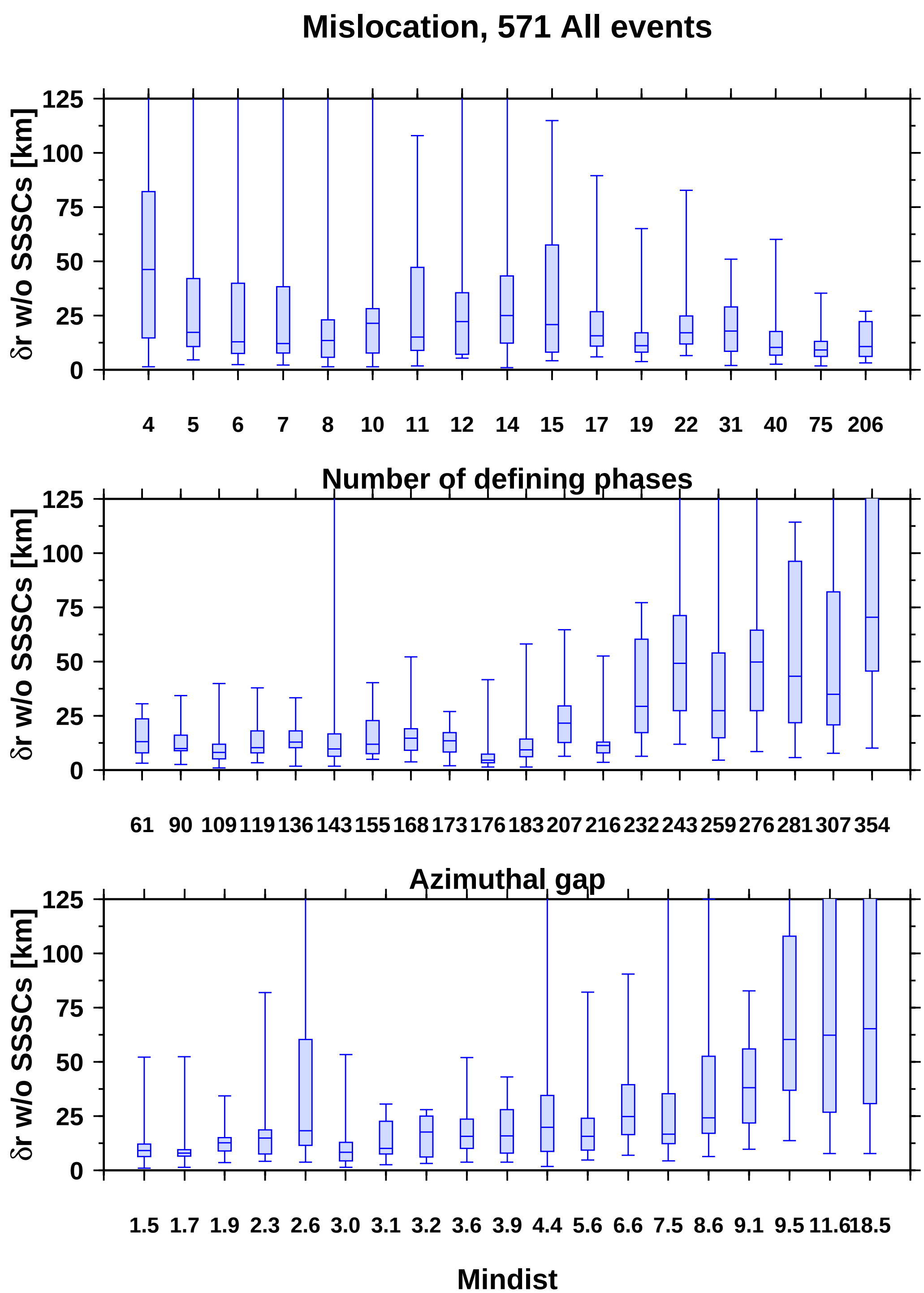


Figure 18d. Mislocations of the GT0-GT10 events without SSSCs versus ndef, azimuthal gap, and minimum distance in degrees (Section 5). In each plot the bins vary according to the cumulative distributions, and only data within 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

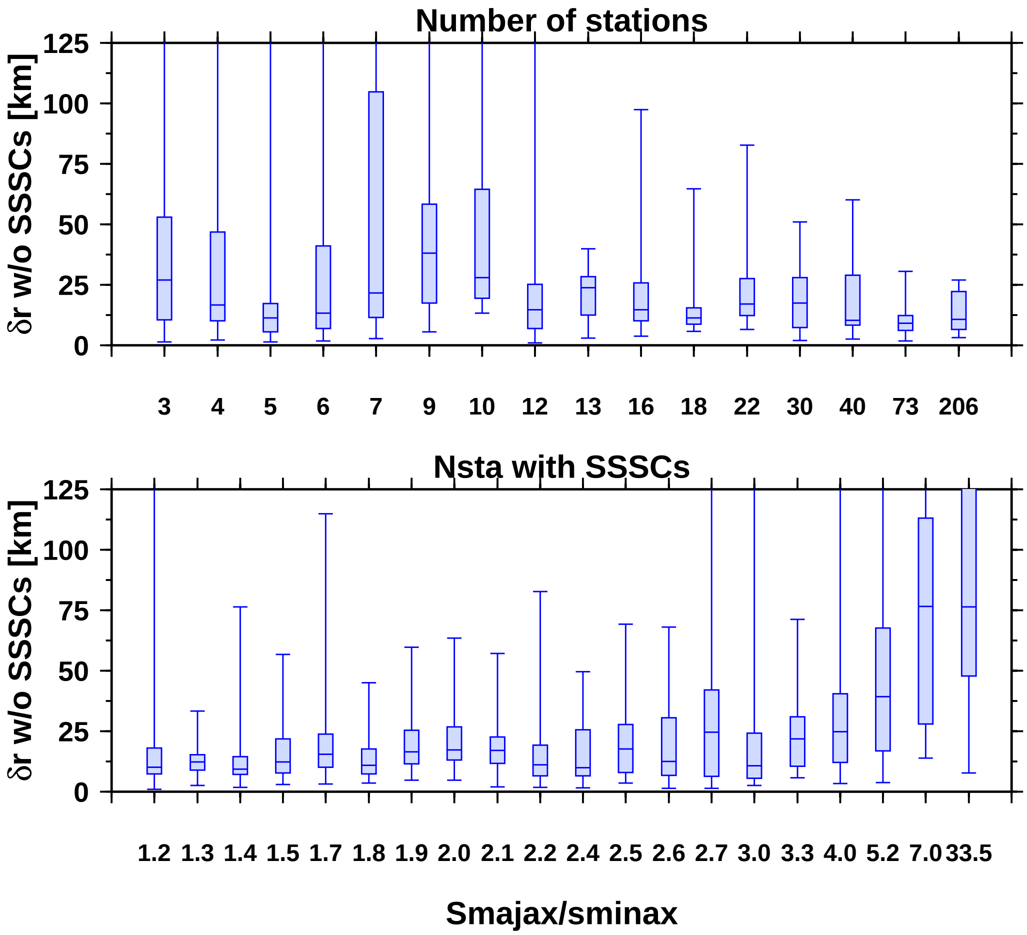


Figure 18e. Mislocations of the GT0-GT10 events without SSSCs versus number of defining stations, number of stations with SSSCs, and error ellipse axis ratio (Section 5). In each plot the bins vary according to the cumulative distributions, and only data within 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

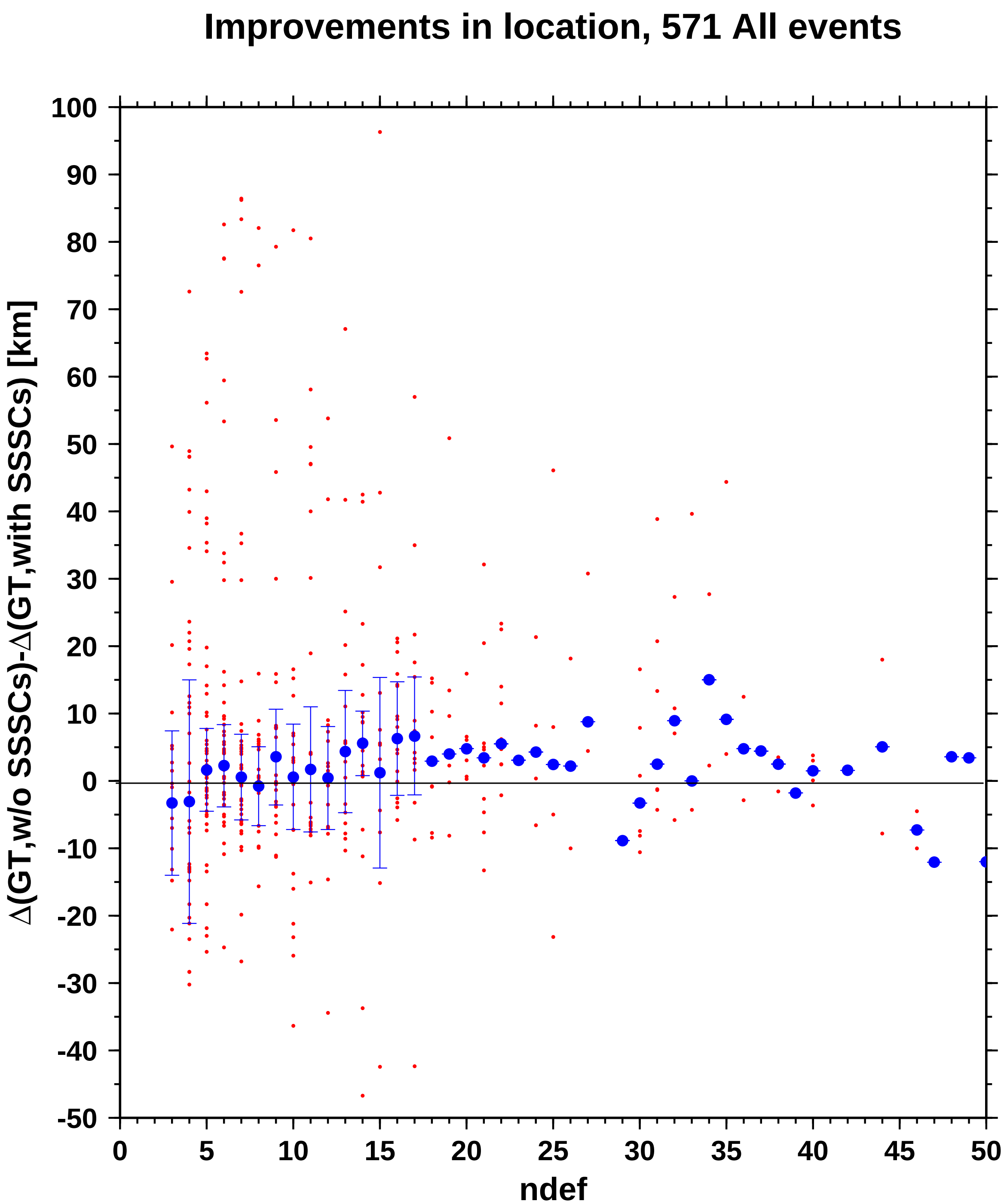


Figure 19. Mislocation improvement vs. ndef for the GT0-GT10 events with and without SSSCs (Section 5). The small red dots are mislocation improvements with SSSCs. The large blue dots are the medians of the ndef groups, and the blue bars are the spreads (when more than 10 observations exist). Positive numbers indicate improvement. While the scattering is large, there are large improvement for low ndef events when SSSCs are applied.

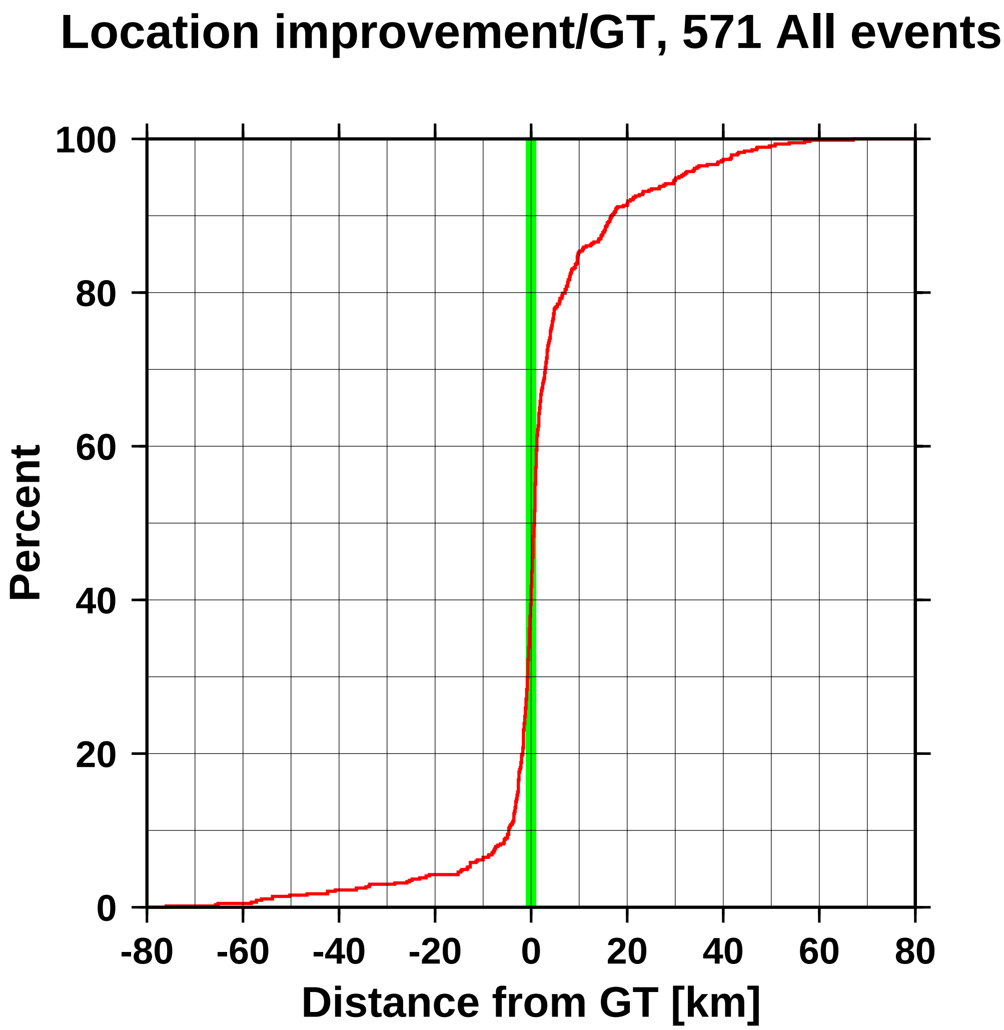


Figure 20a. Mislocation improvement, scaled by GT accuracy, for the GT0-GT10 events when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1).About 31% are uncertain, i.e. within the GT accuracy. About 43% events are improved (40% more events), compared to about 26% events are deteriorated.

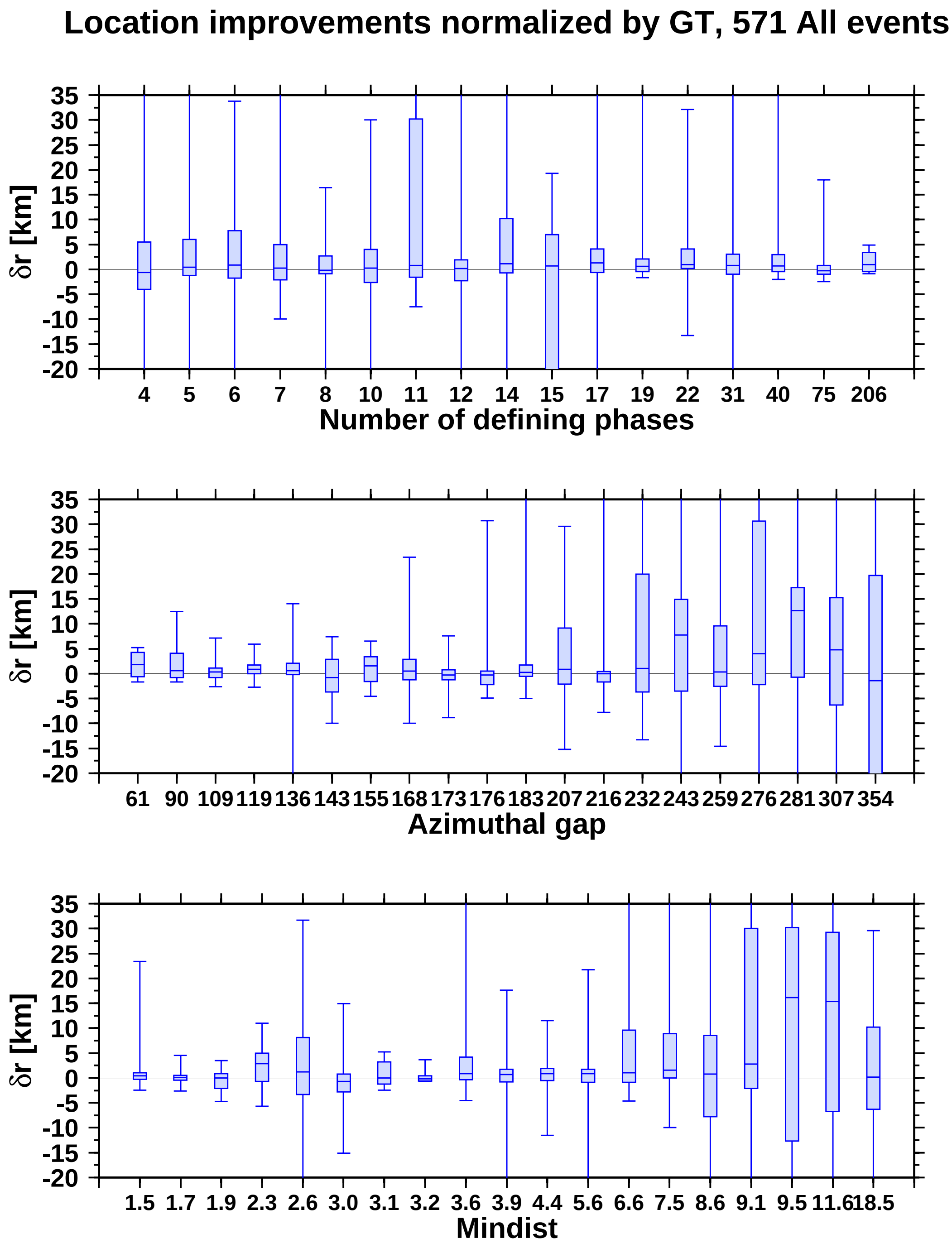


Figure 20b. Mislocation improvement, scaled by GT accuracy, of the GT0-GT10 events with SSSCs versus ndef, azimuthal gap, and minimum distance in degrees (Section 5). In each plot the bins vary according to the cumulative distributions, and only data within 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

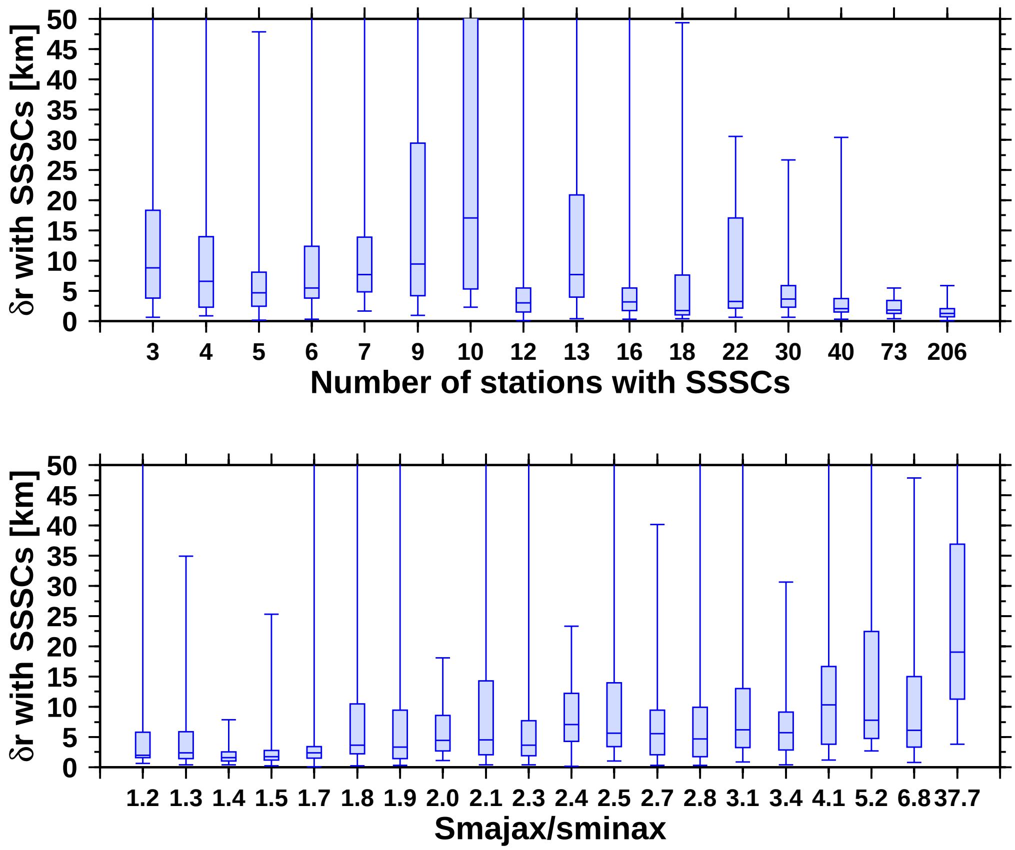


Figure 20c. Mislocation improvement, scaled by GT accuracy, of the GT0-GT10 events with SSSCs versus number of defining stations with SSSCs and error ellipse axis ratio (Section 5). In each plot the bins vary according to the cumulative distributions, and only data within 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

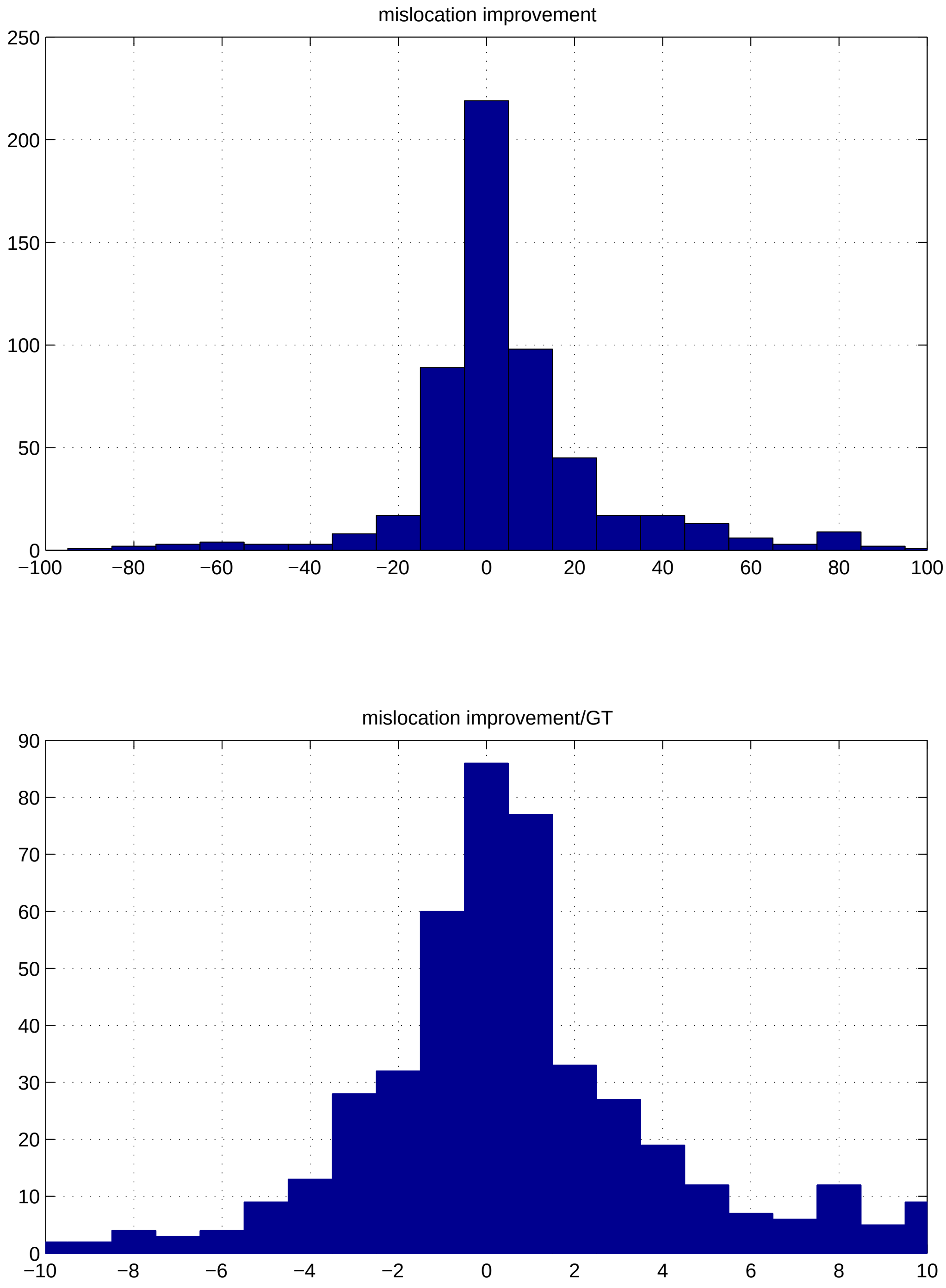


Figure 20d. Histograms of mislocations improvement of the GT0-GT10 events when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). In the bottom plot mislocation is scaled by GT accuracy, assuming GT0 as GT1.

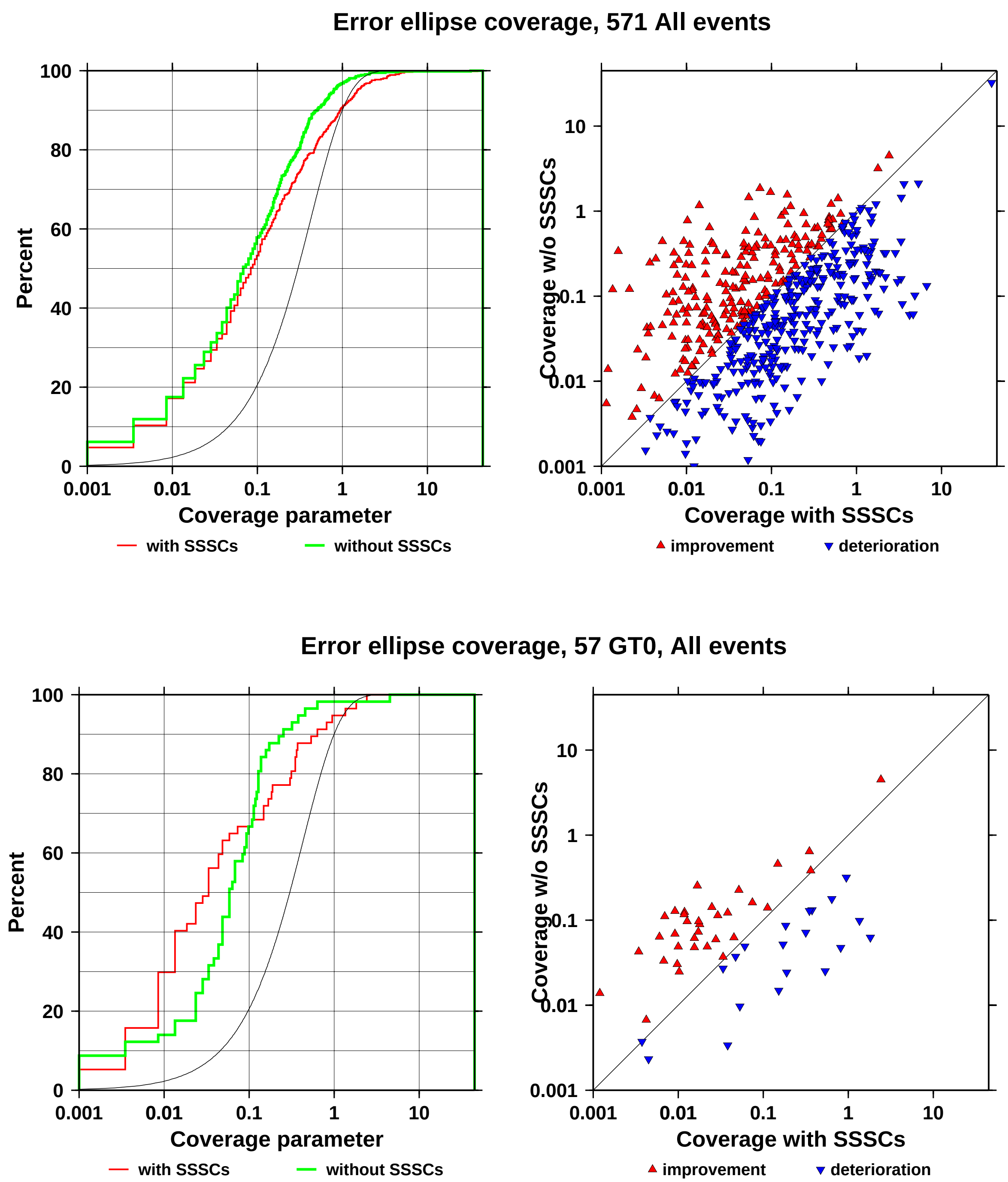


Figure 21a. Ellipse coverages of all GT0-GT10 (Top) and GT0 (Bottom) events with and without SSSCs (Section 5). (Left) Cumulative plot of error ellipse coverage. The χ^2distribution is also plotted. (Right) Comparisons of ellipse coverage with (red triangle) and without (blue inverse triangle) SSSCs. Symbols above the diagonal line indicate improvement with SSSCs.

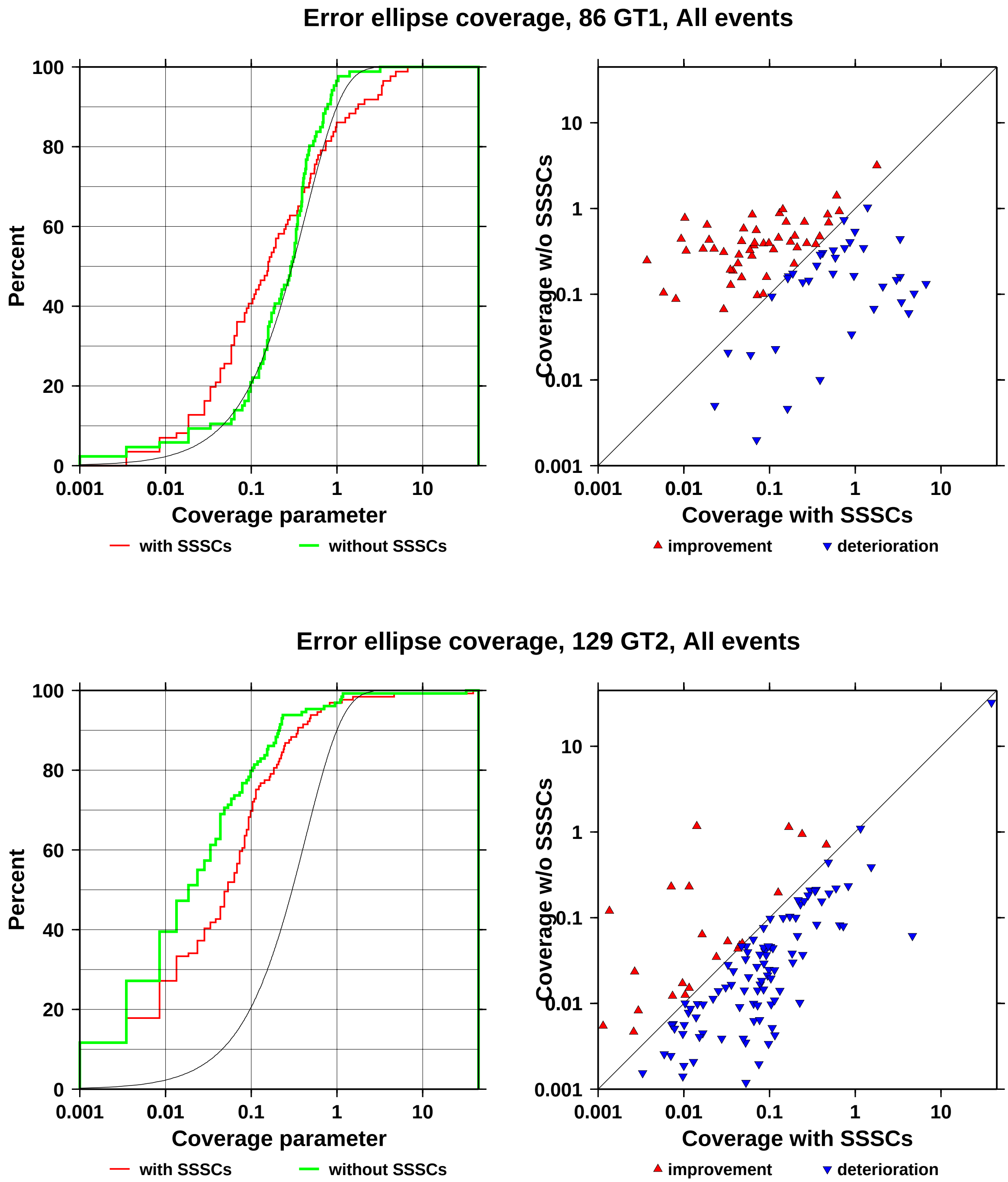
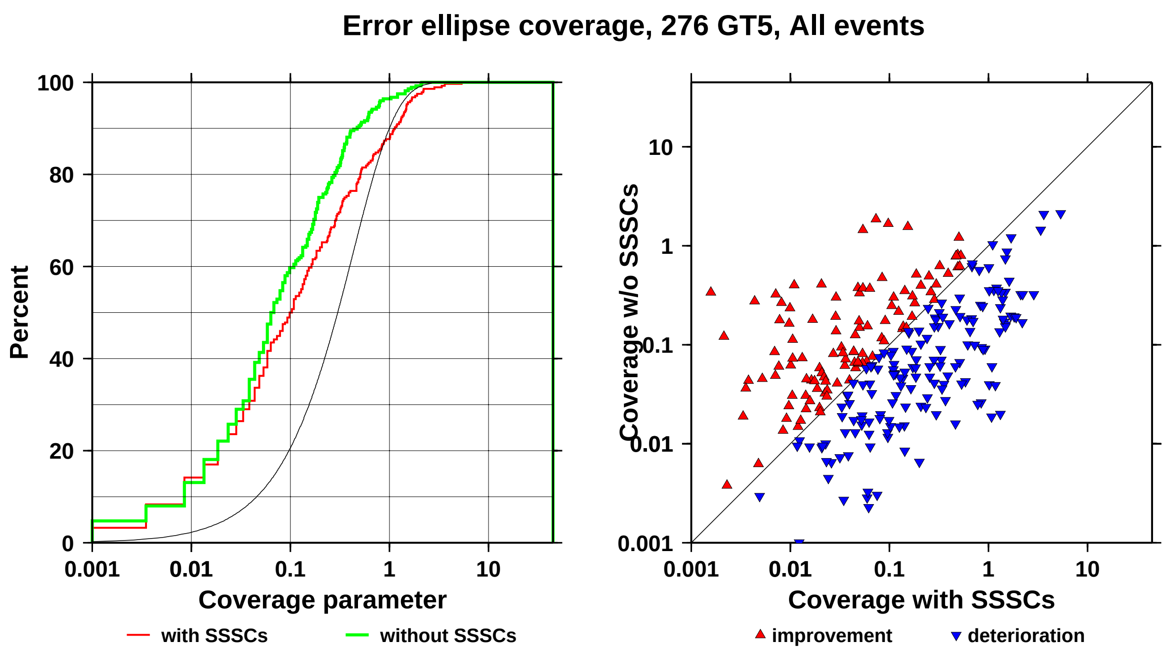


Figure 21b. Ellipse coverages of GT1 (Top) and GT2 (Bottom) events with and without SSSCs (Section 5). (Left) Cumulative plot of error ellipse coverage. The χ^2distribution is also plotted. (Right) Comparisons of ellipse coverage with (red triangle) and without (blue inverse triangle) SSSCs. Symbols above the diagonal line indicate improvement with SSSCs.



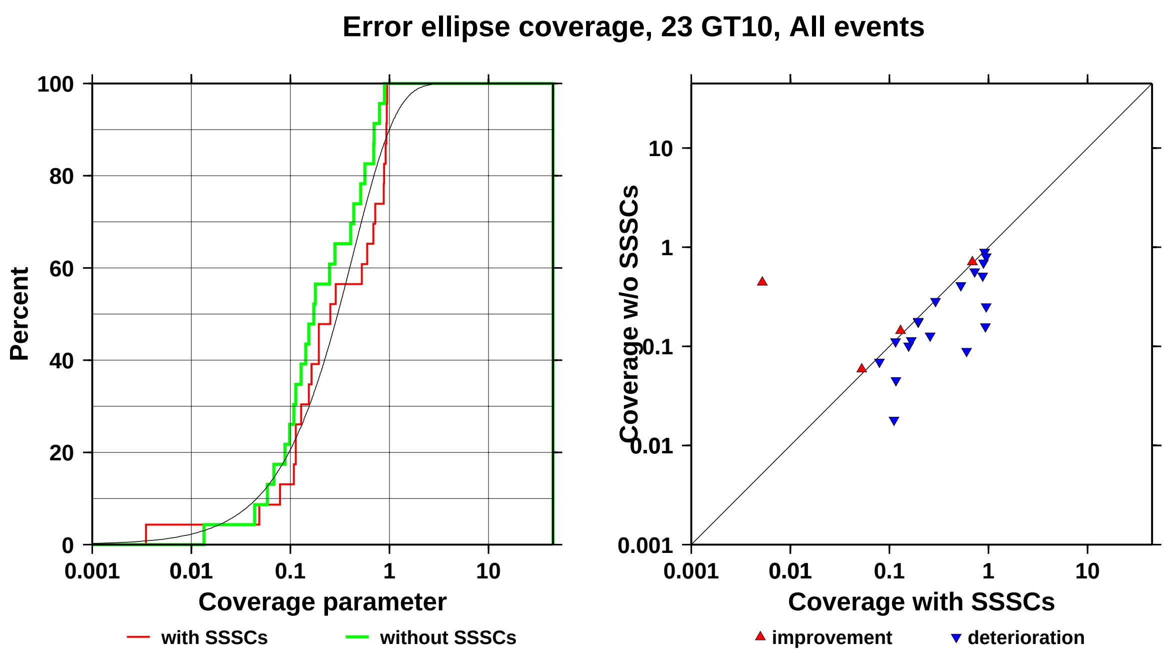


Figure 21c. Ellipse coverages of GT5 (Top) and GT10 (Bottom) events with and without SSSCs (Section 5). (Left) Cumulative plot of error ellipse coverage. The χ^2distribution is also plotted. (Right) Comparisons of ellipse coverage with (red triangle) and without (blue inverse triangle) SSSCs. Symbols above the diagonal line indicate improvement with SSSCs.

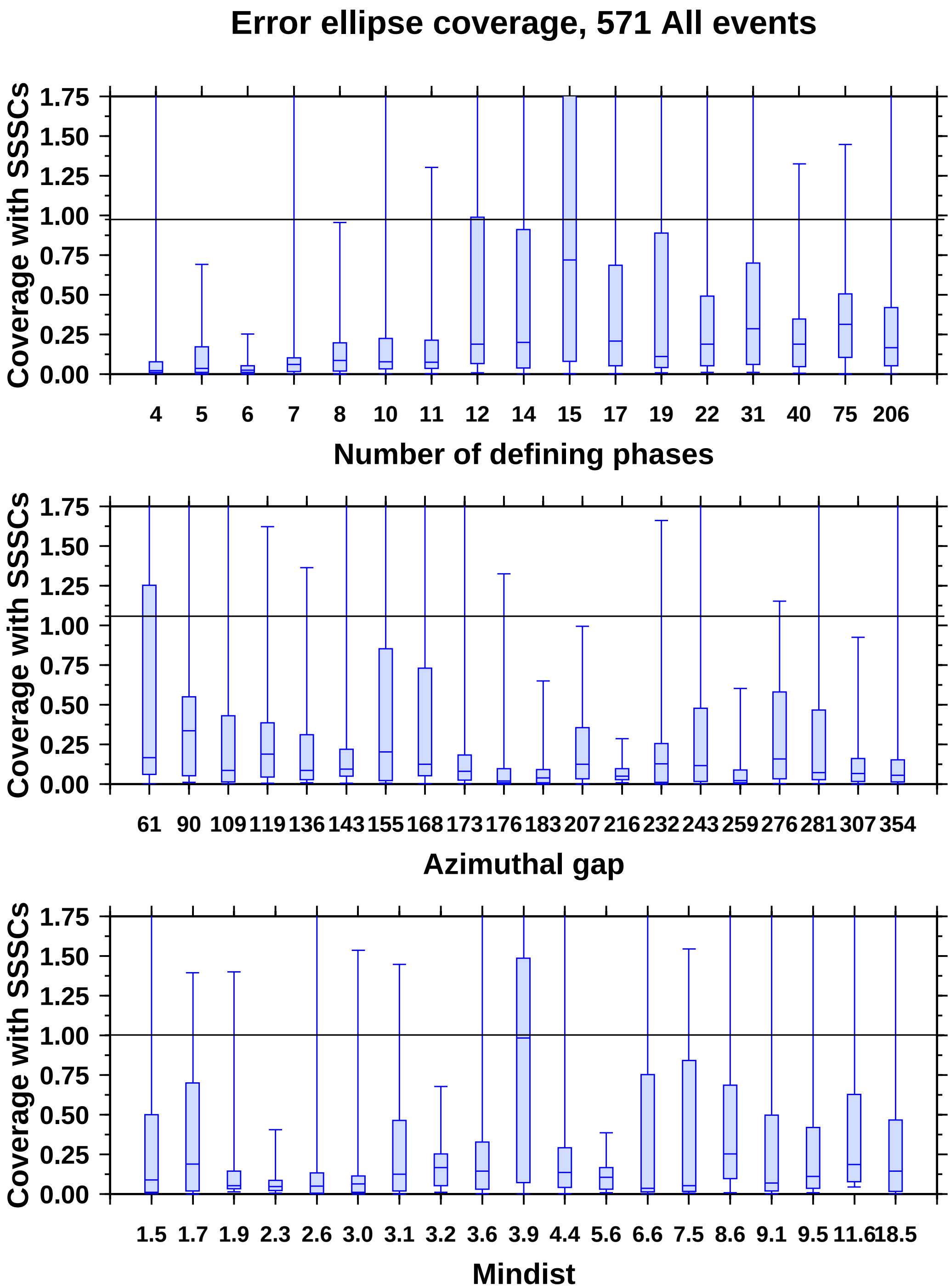


Figure 22a. 90% coverages of the GT0-GT10 events with SSSCs versus ndef, azimuthal gap, and minimum distance in degrees (Section 5). In each plot the bins vary according to the cumulative distributions, and only data within the 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

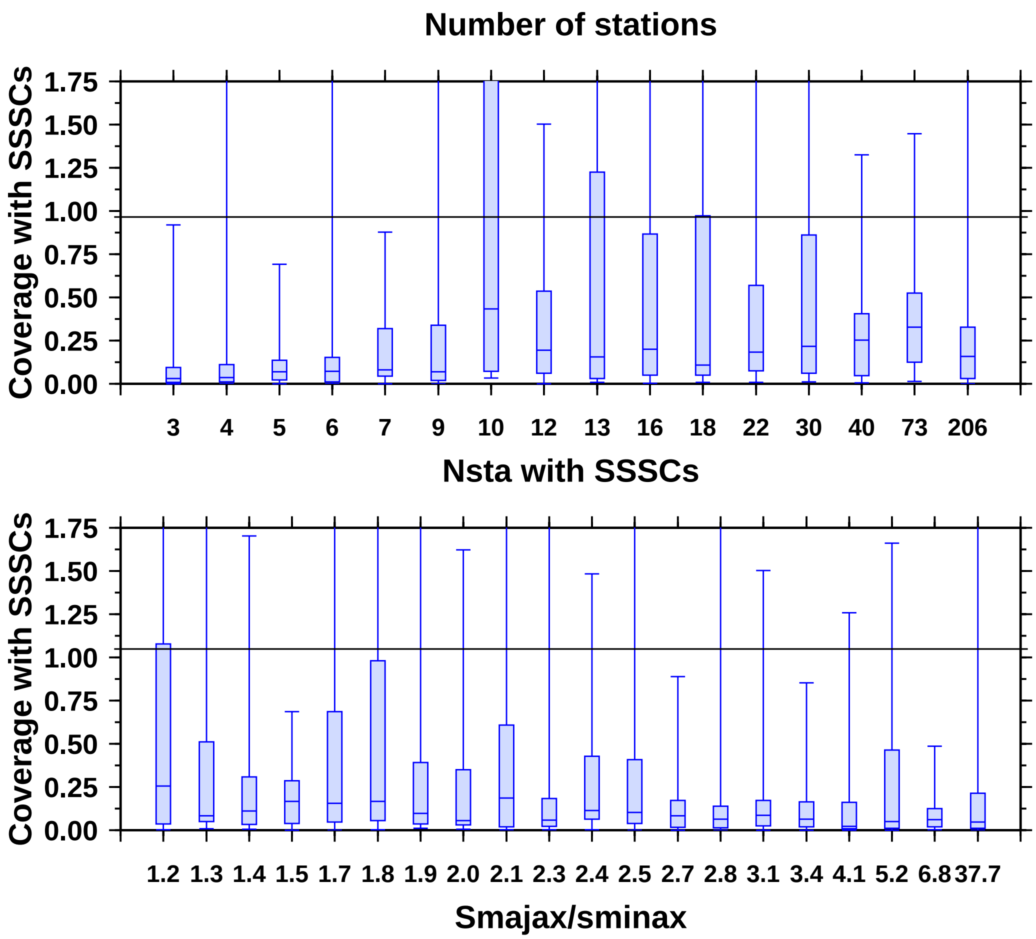


Figure 22b. 90% coverages of the GT0-GT10 events with SSSCs versus number of stations with SSSCs and error ellipse axis ratio (Section 5). In each plot the bins vary according to the cumulative distributions, and only data within the 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

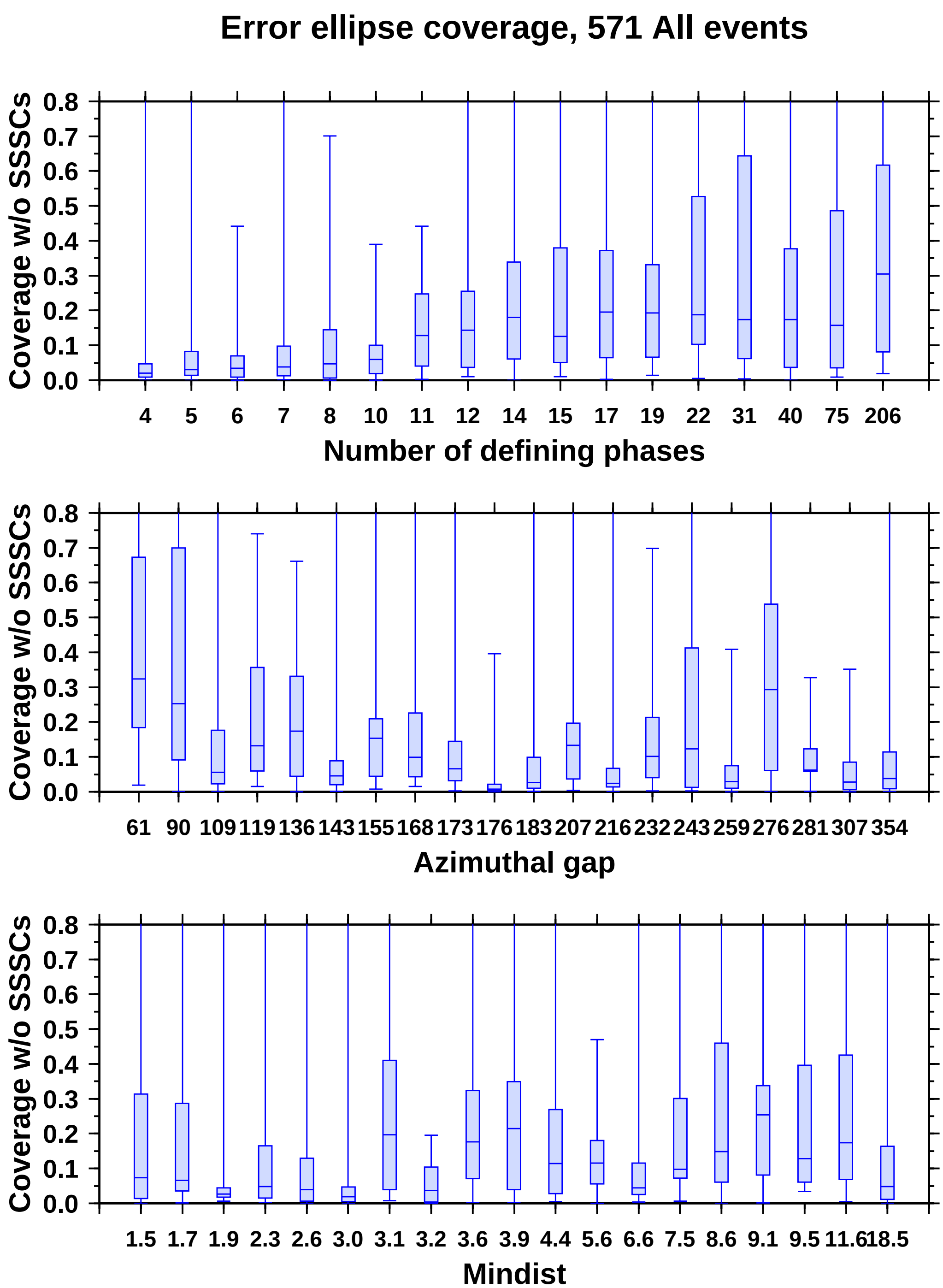


Figure 22c. 90% coverages of the GT0-GT10 events without SSSCs versus ndef, azimuthal gap, and minimum distance in degrees (Section 5). In each plot the bins vary according to the cumulative distributions, and only data within the 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

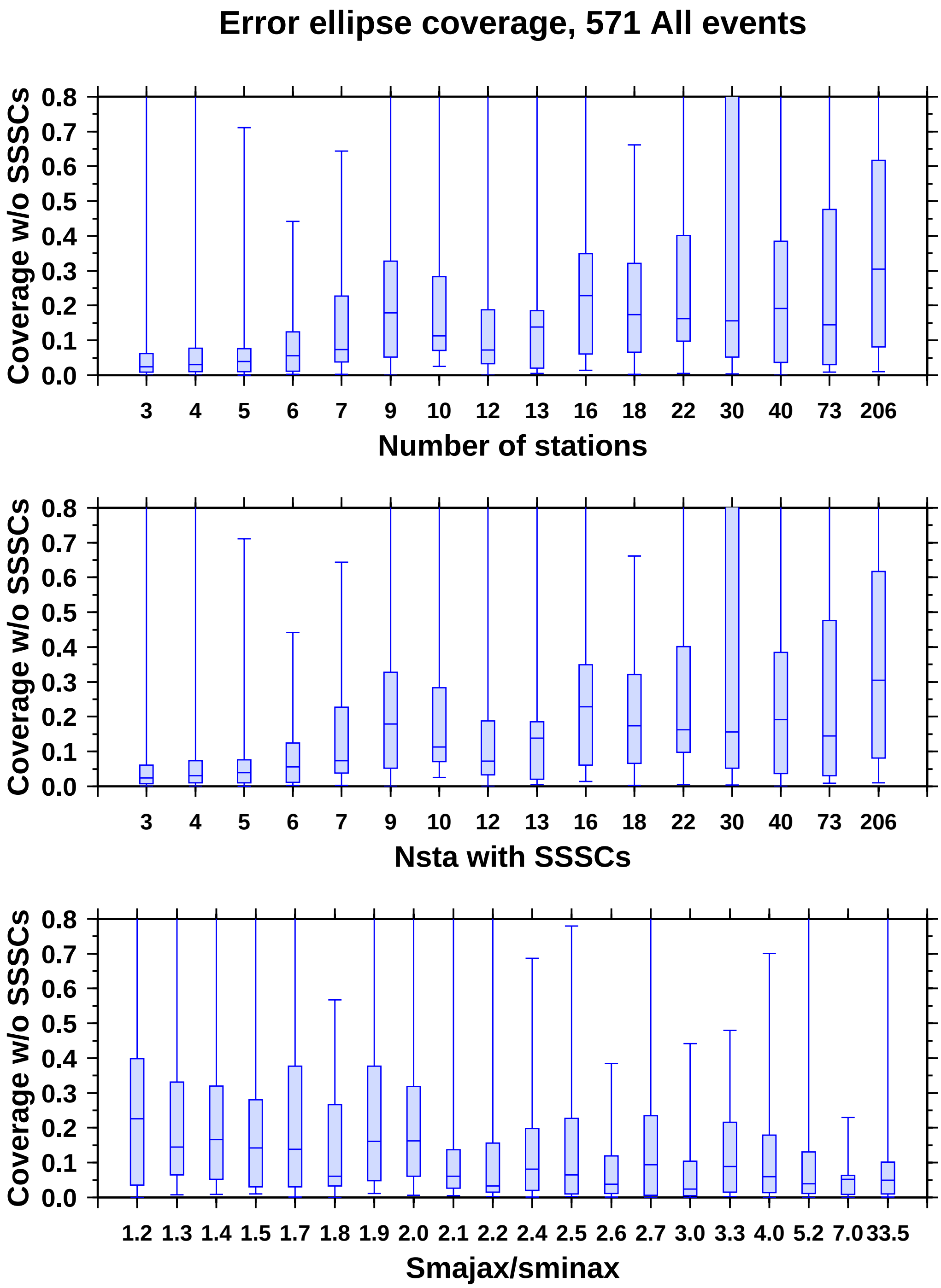


Figure 22d. 90% coverages of the GT0-GT10 events without SSSCs versus ndef, azimuthal gap, and error ellipse axis ratio (Section 5). For this test the first two plots are the same. In each plot the bins vary according to the cumulative distribution, and only data within the 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

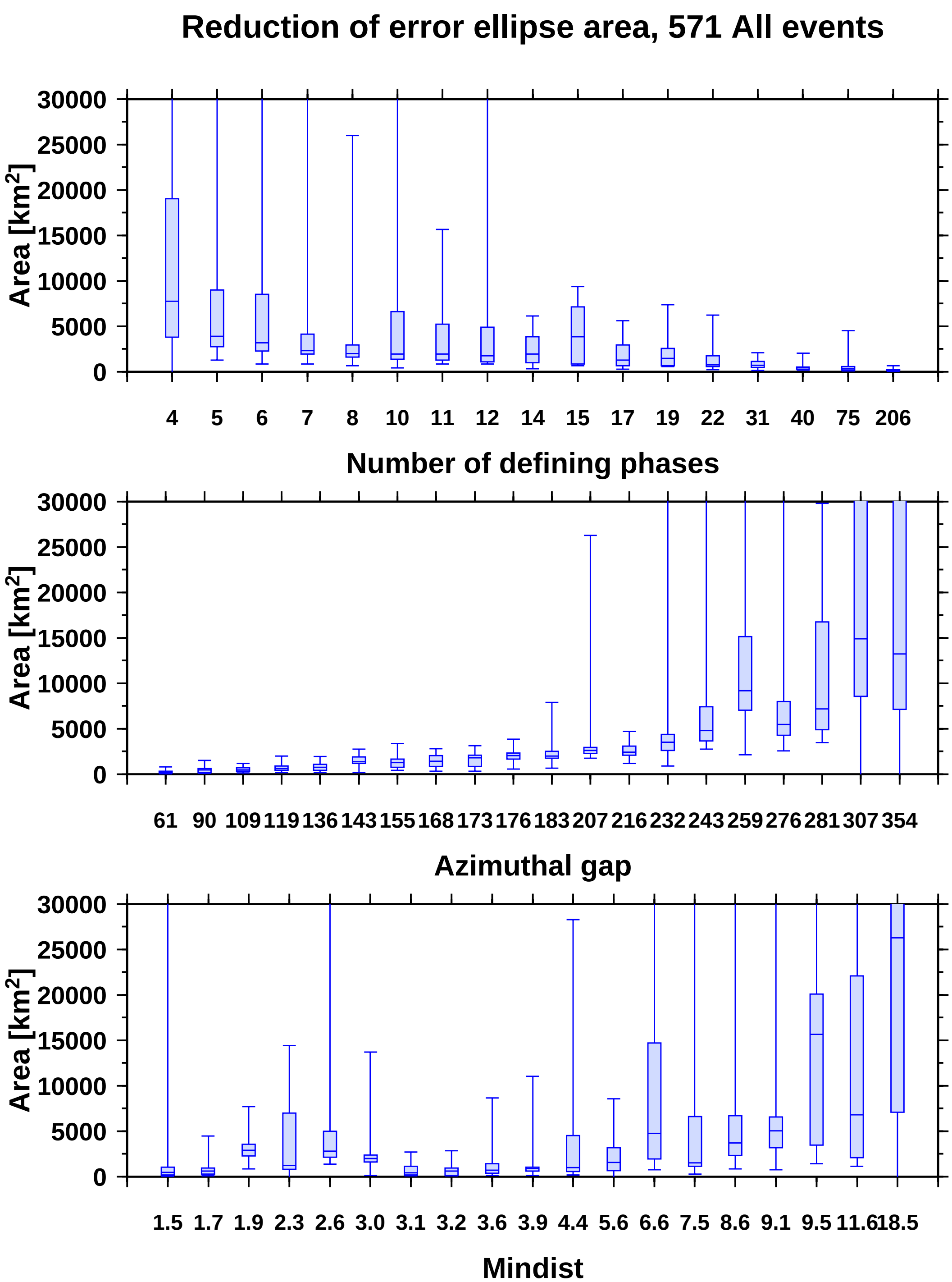


Figure 23. Improvement on error ellipse areas of the GT0-GT10 events with and without SSSCs versus ndef, azimuthal gap, and error ellipse axis ratio (Section 5). In each plot the bins vary according to the cumulative distribution, and only data within the 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

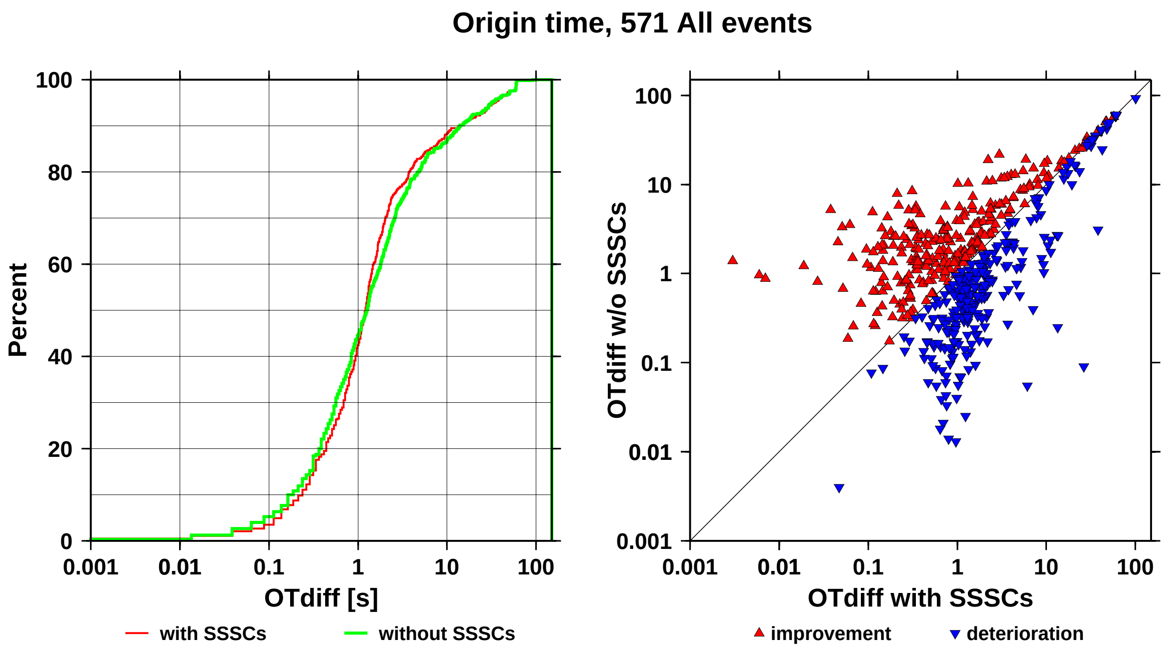


Figure 24a. Origin time of the GT0-GT10 events with and without SSSCs (Section 5.1). (Left) Cumulative plot of origin time. (Right) Comparisons of origin times with (red triangle) and without (blue inverse triangle) SSSCs. Symbols above the diagonal line indicate improvement with SSSCs.

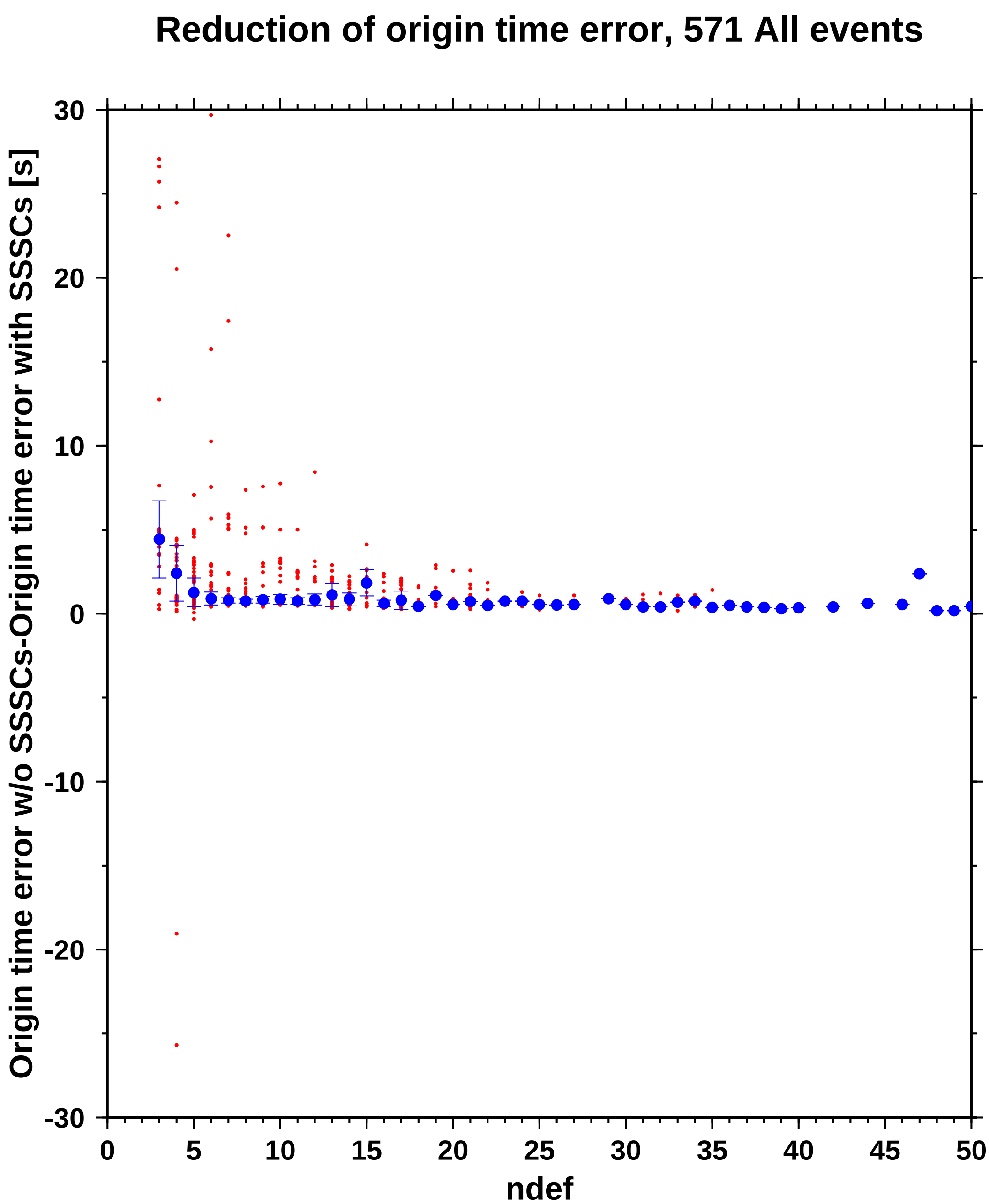


Figure 24b. Improvement of origin time errors vs. ndef for the GT0-GT10 events with and without SSSCs (Section 5.1). The small red dots are mislocation improvements with SSSCs. The large blue dots are the medians of the ndef groups, and the blue bars are the spreads (when more than 10 observations exist).

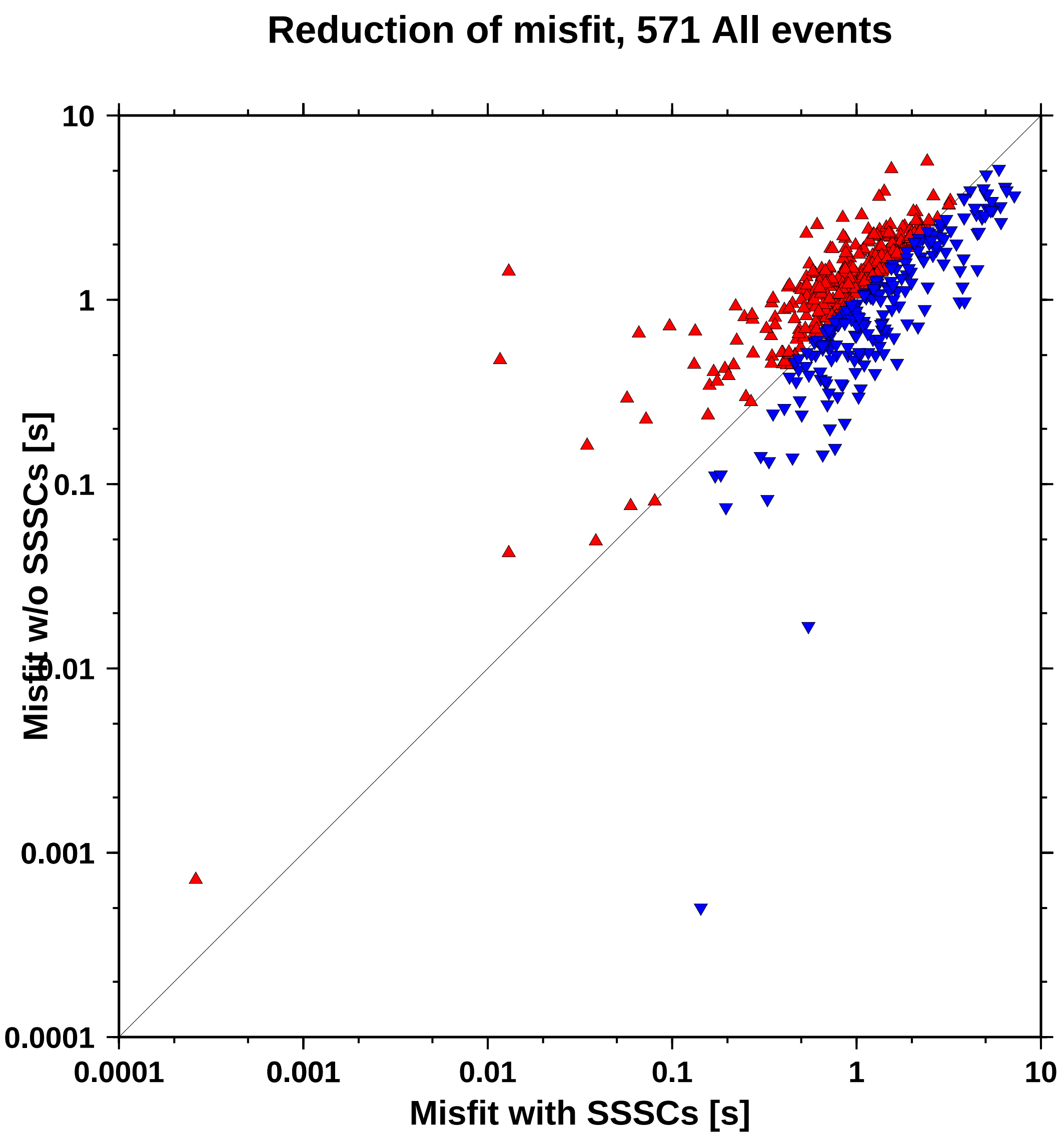


Figure 25. Standard errors of observations (misfit) of the GT0-GT10 events with (red triangle) and without (blue inverse triangle) SSSCs (Section 5.1).

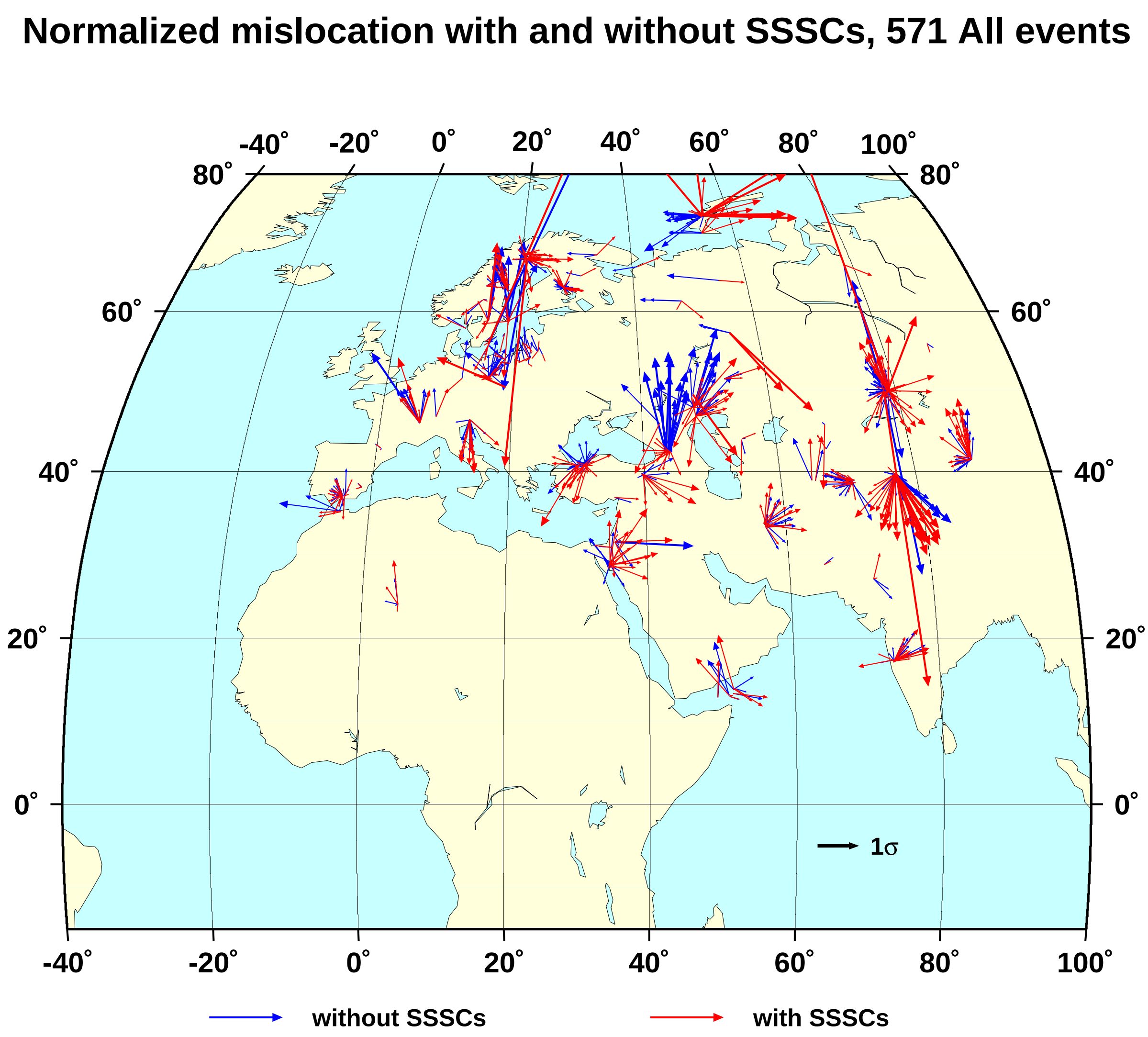


Figure 25a. Normalized mislocations with (red) and without (blue) SSSCs when the GT0-GT10 events are relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). The direction of the arrows are from the GT to the relocation. The baseline scale is 1, i.e. 90% coverage is met.

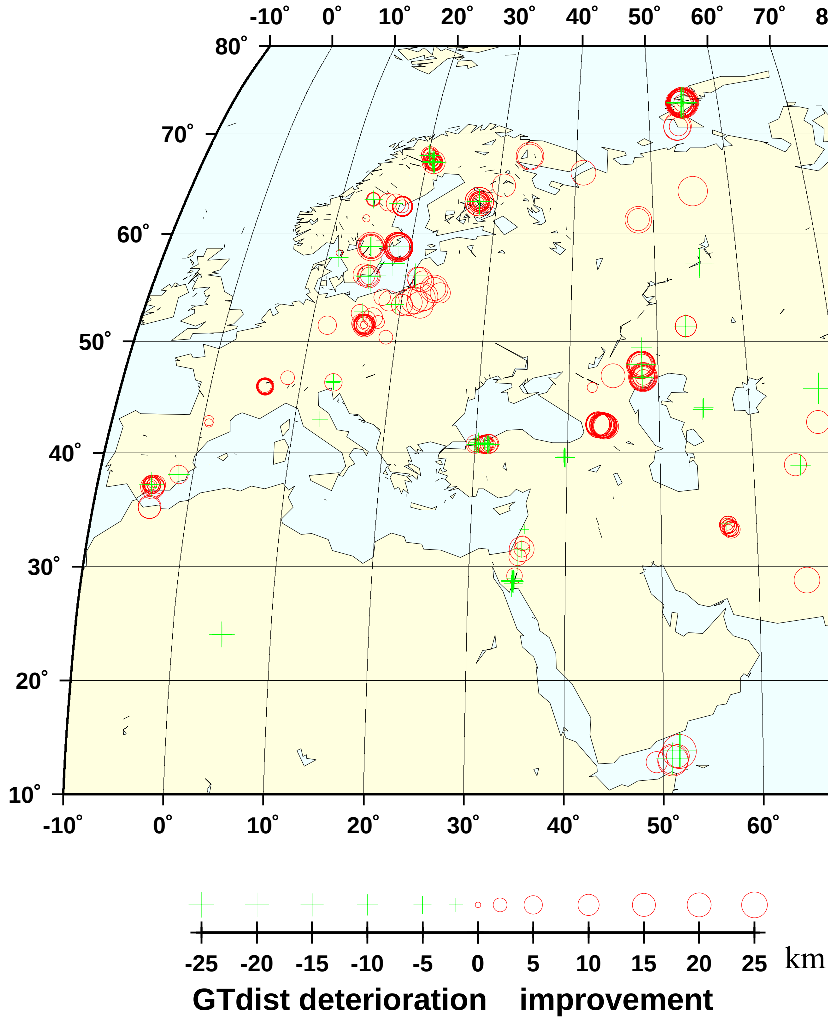


Figure 25b. The deterioration (green cross) and improvement (red circle) in mislocation of the Group-2 GT0-GT10 data set when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). The symbol size indicates the degree of improvement or deterioration.

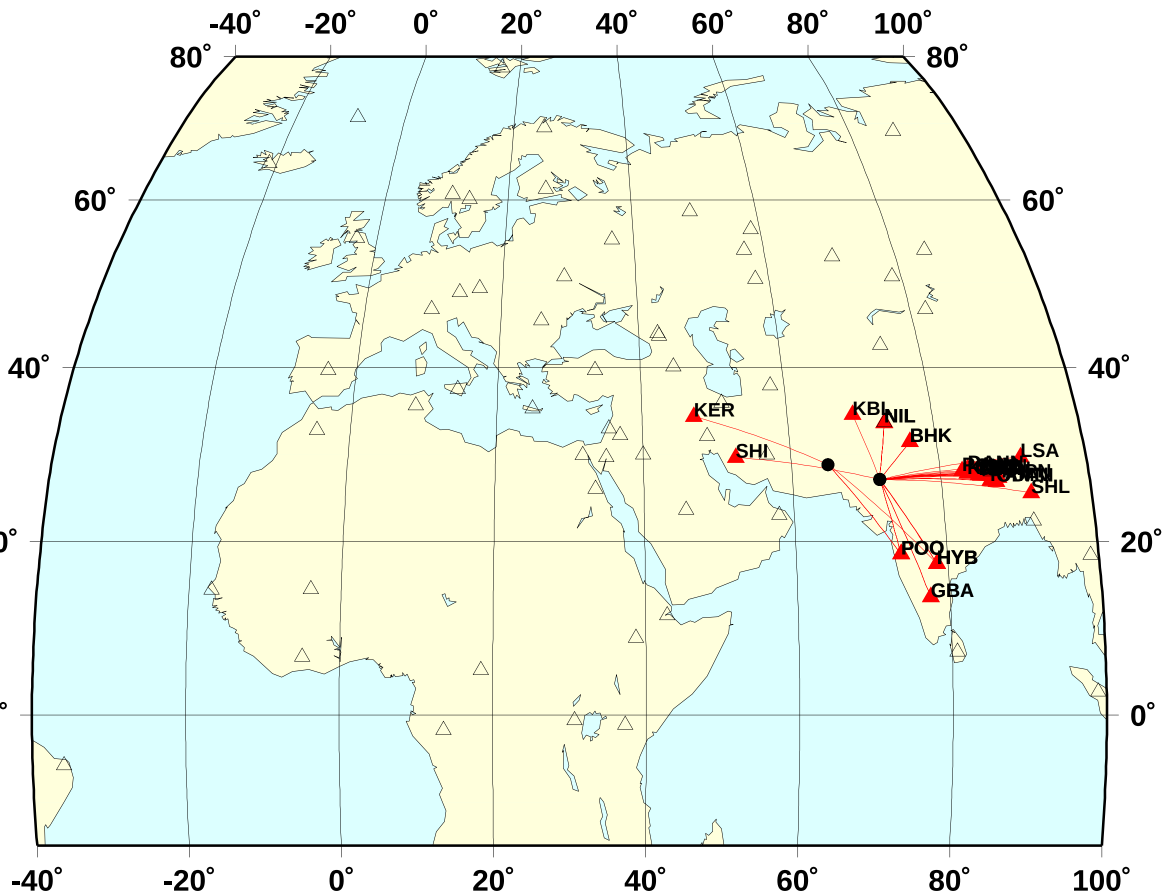


Figure 26a. The Indian and Pakistan nuclear explosions in the Group-2 GT0-GT10 data set relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). They are GT0-GT1 events with arrivals from the EHB catalog. Station event paths for defining Pn and Sn phases are plotted. Stations are shown as solid triangles and events are shown as solid circles. IMS stations are also plotted on the map (open triangles).

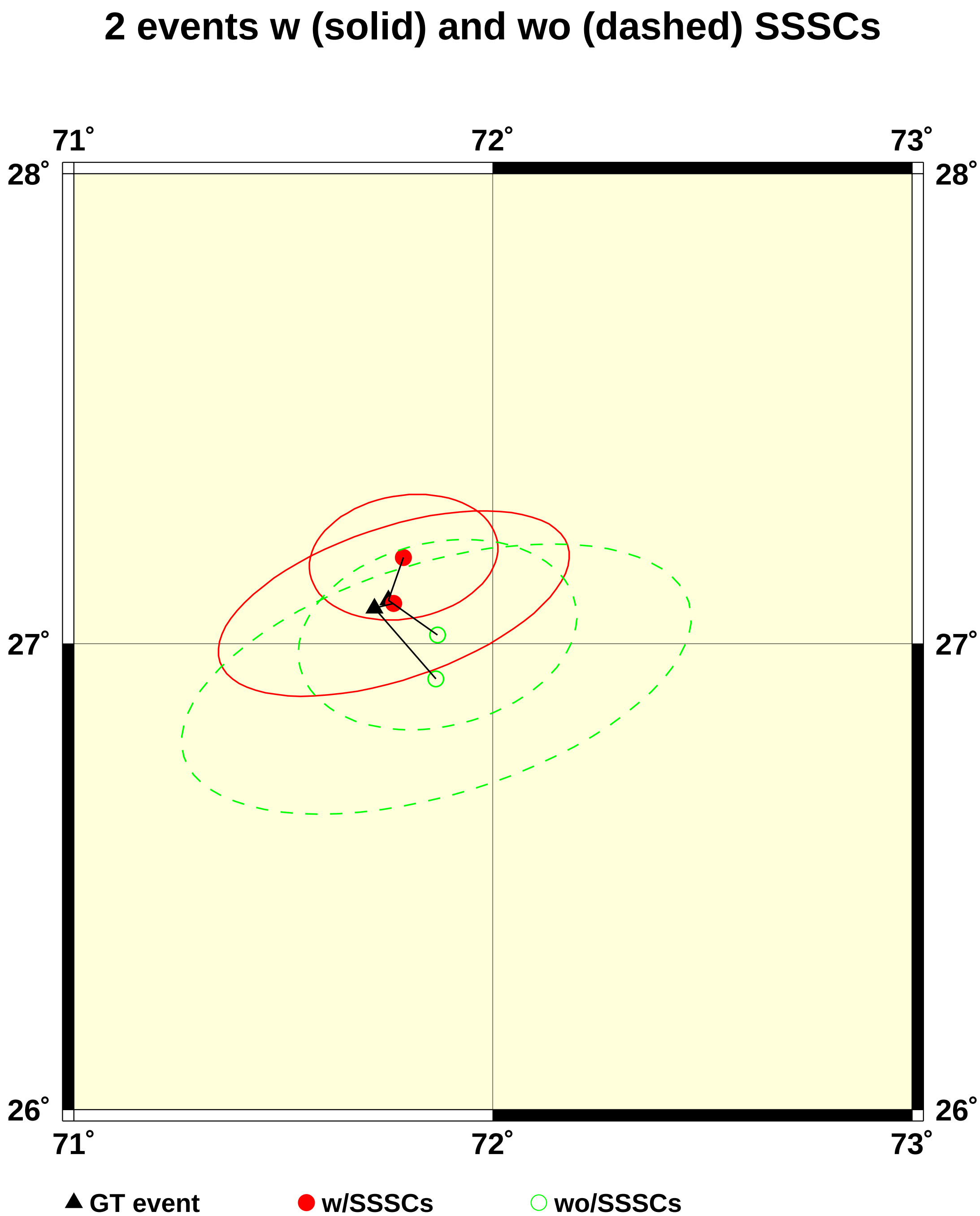


Figure 26b. Locations of the Indian nuclear explosions in the Group-2 GT0-GT10 data set when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). Event locations, error ellipses with (solid) and without (open/dashed) SSSCs, and GT locations for the two GT0-GT1 events are all plotted. For the 1974 and 1998 explosions, with SSSCs the location is within 10.8 km and 4.6 km, respectively, from the GT, improved by 3.4 km and 17.6 km, respectively, compared without SSSCs.

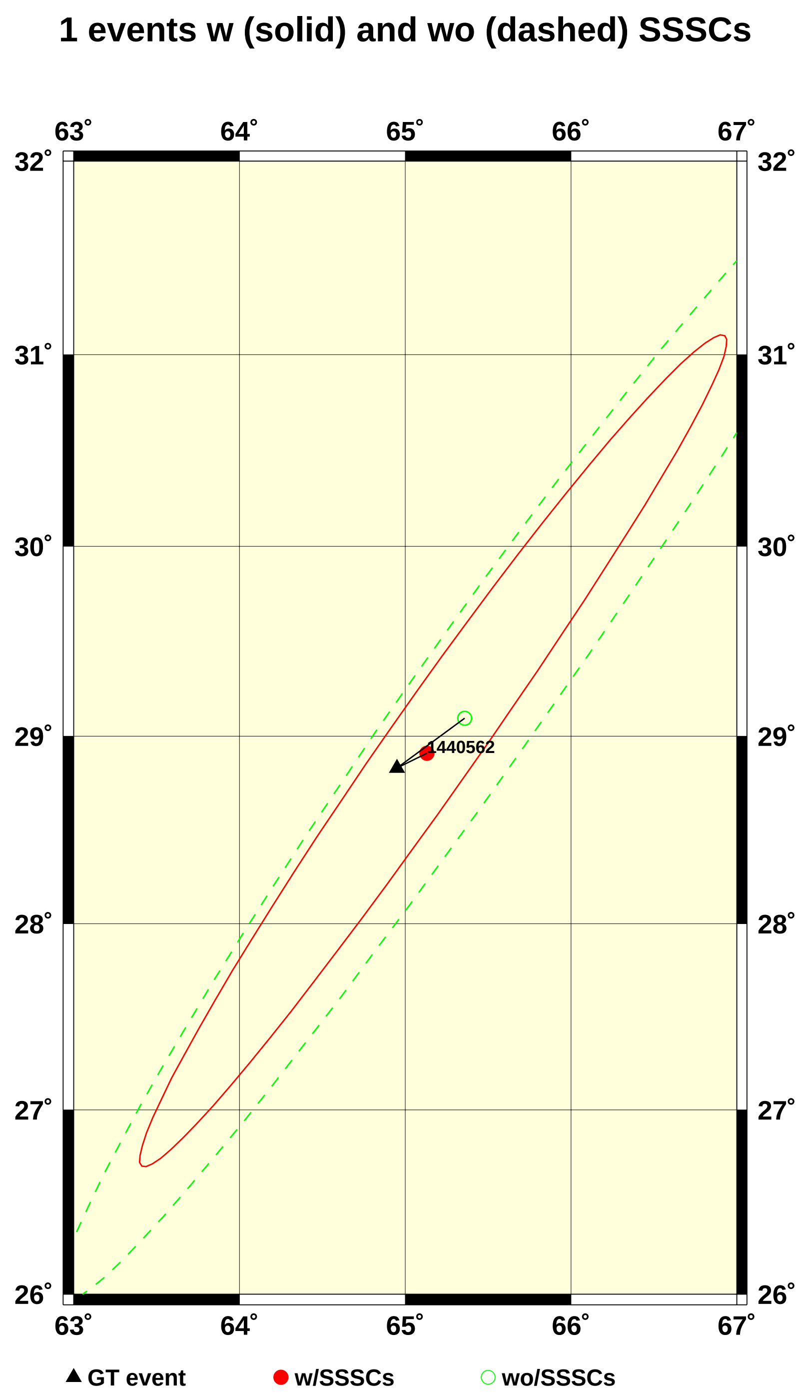


Figure 26c. Locations of the 1998/5/28 Pakistan nuclear explosion in the Group-2 GT0-GT10 data set when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). Event locations, error ellipses with (solid) and without (open/dashed) SSSCs, and the GT location for the GT1 event are all plotted. With SSSCs the location is located within 19.8 km from the GT, improved by 29.6 km compared without SSSCs. The error ellipses are large because the locations are based on only three stations that are poorly distributed.

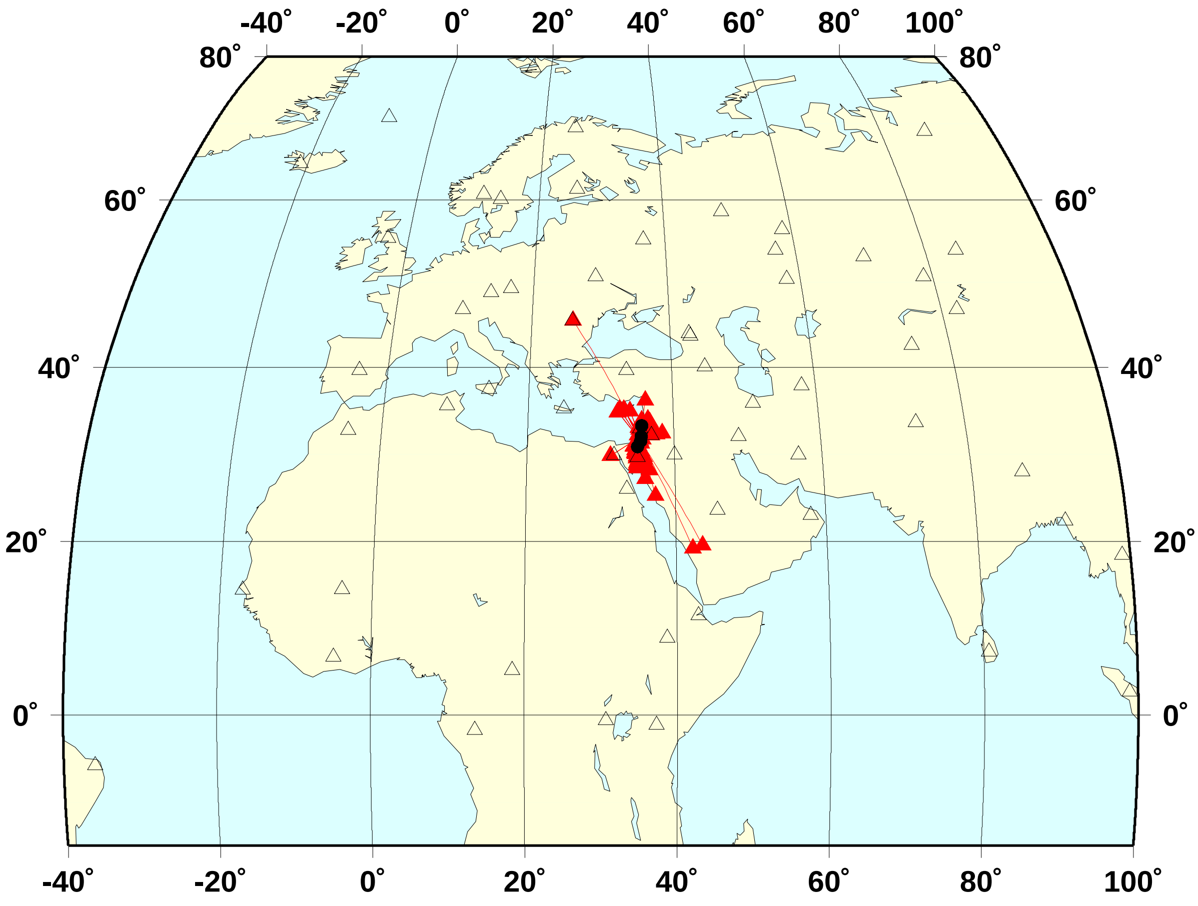


Figure 27a. The Israeli events in the Group-2 GT0-GT10 data set when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). These are GT0-GT5 events from GII. Station-event paths for defining Pn and Sn phases are plotted. Stations are shown as solid triangles and events are shown as solid circles. IMS stations are also plotted on the map (open triangles).

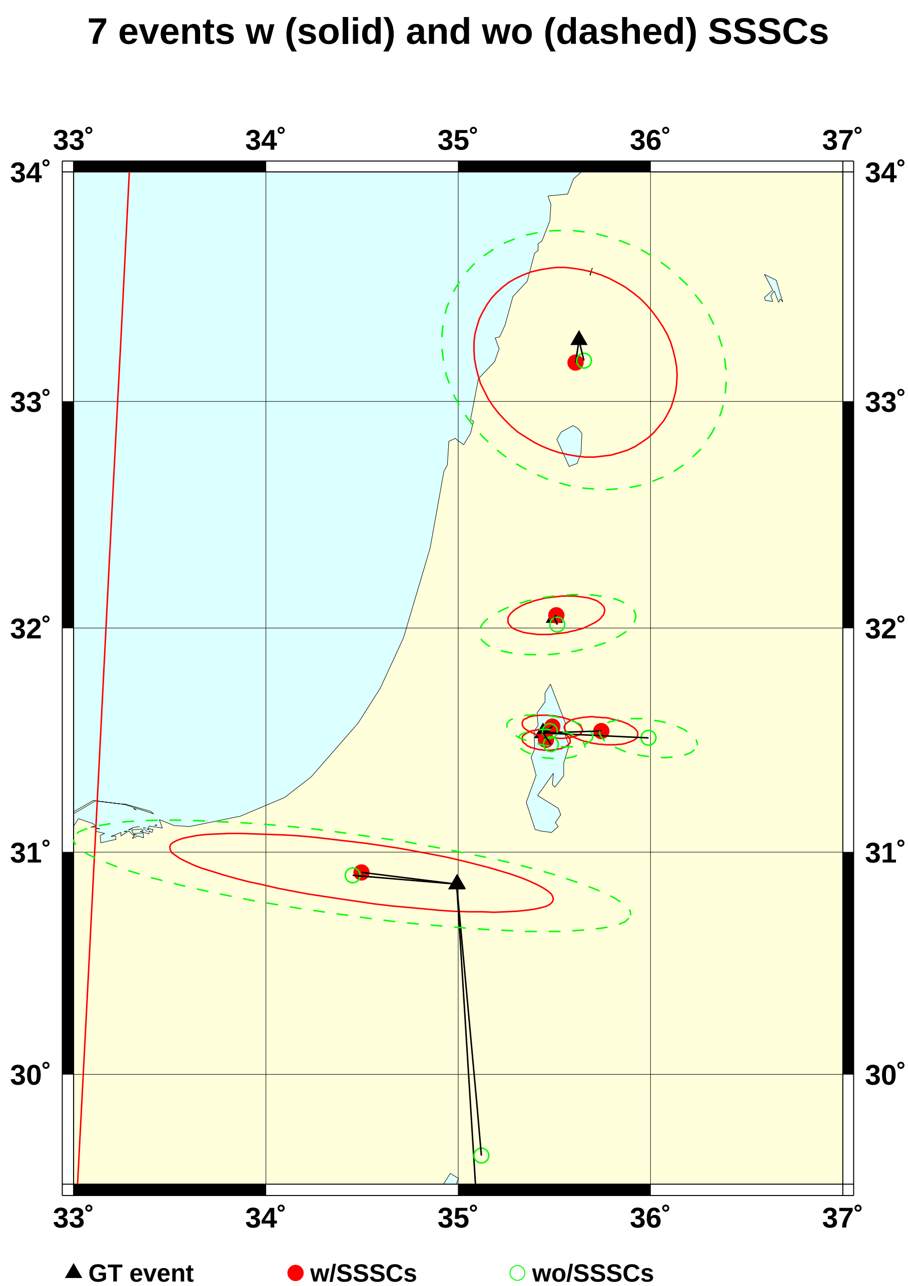


Figure 27b.Locations of the Israeli events in the Group-2 GT0-GT10 data set when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). Event locations, error ellipses with (solid) and without (open/dashed) SSSCs, and GT locations for the 7 GT0-GT5 events are all plotted. For the two co-located Israeli quarry blasts (southernmost events), one event with poor station distribution has larger mislocation compared to the other one. For the two earthquakes (northernmost events), again one event with poor station geometry is not as well located compared to the other one. Two of the three Dead Sea shots are improved with SSSCs, but the 1999/11/10 event is mislocated by 5.6 km with SSSCs, worse by 2 km. With the Saudi data the 1999/11/11 event was located better with SSSCs than without SSSCs (Figure 27c).

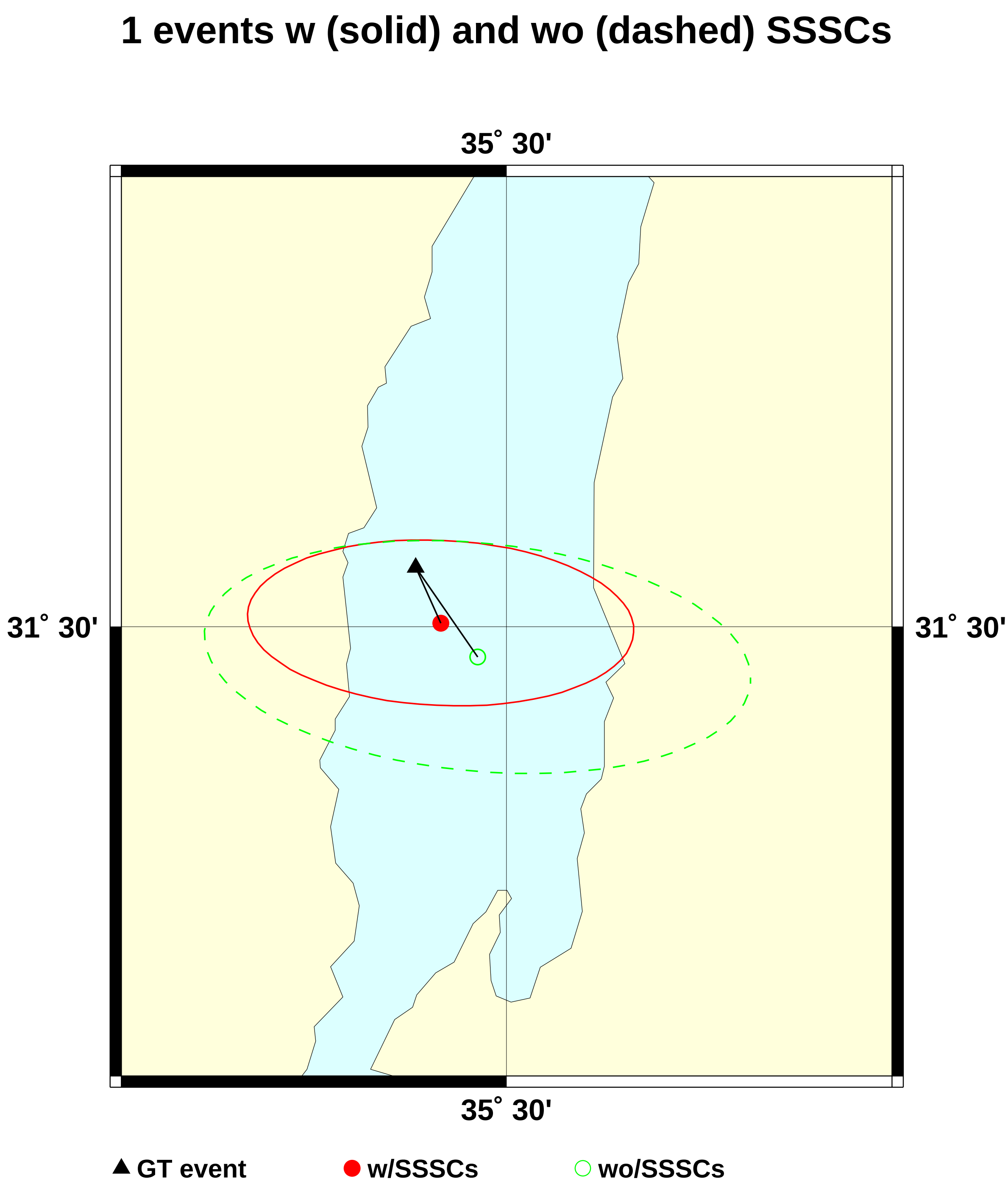


Figure 27c. Locations of the 1999/11/11 Dead Sea shot in the Group-2 GT0-GT10 data set when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). Event locations, error ellipses with (solid) and without (open/dashed) SSSCs, and GT locations for the GT0 event are also plotted. With SSSCs the median mislocation is 3.8 km, improved by 2.9 km.

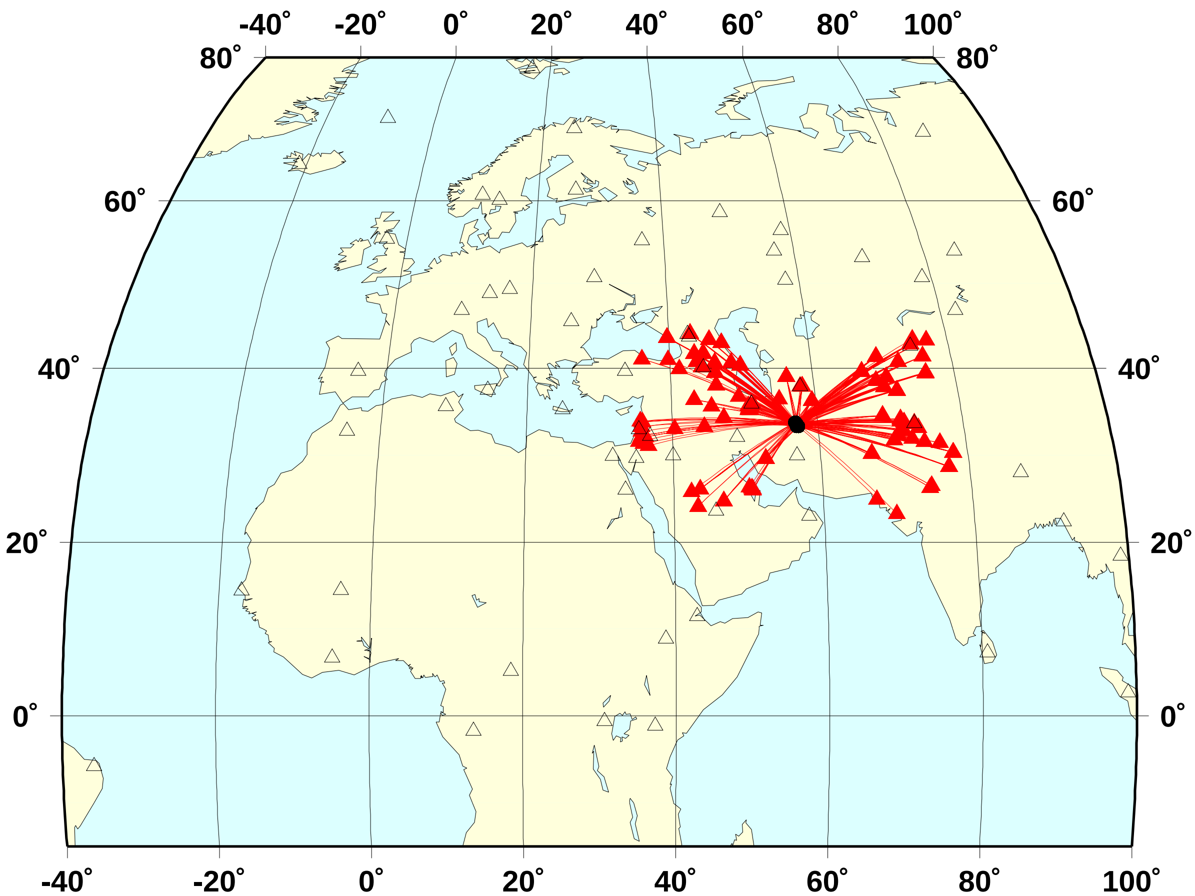


Figure 28a. The Tabas cluster in the Group-2 GT0-GT10 data set relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). These are GT5 cluster events from the HDC analysis and only Pn phases are present. Station-event paths for defining Pn phases are plotted. Stations are shown as solid triangles and events are shown as solid circles. IMS stations are also plotted on the map (open triangles).

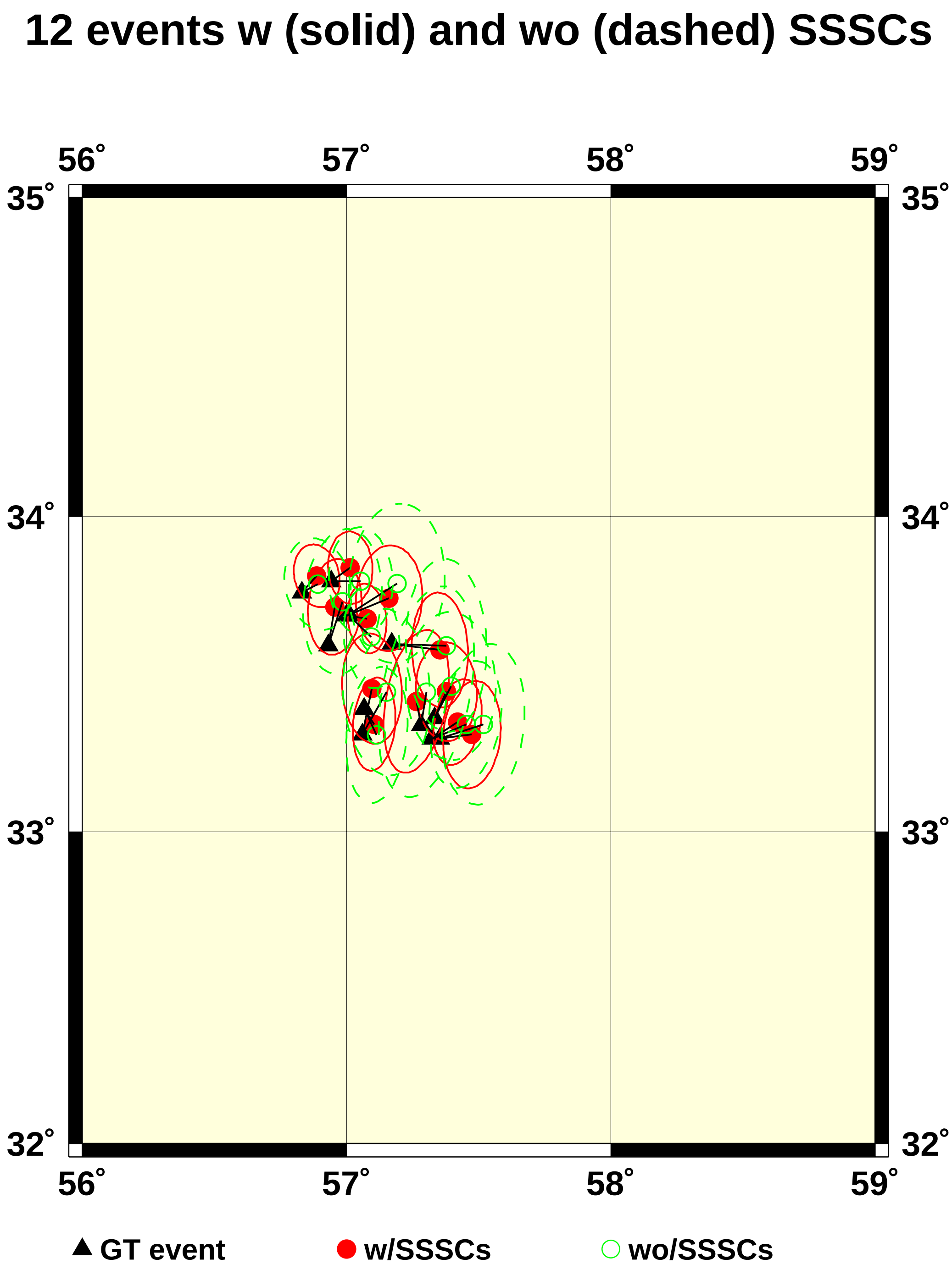


Figure 28b. Locations of the Tabas cluster in the Group-2 GT0-GT10 data set when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). Event locations, error ellipses with (solid) and without (open/dashed) SSSCs, and GT locations for the 12 GT5 events are also plotted. One event is deteriorated with a mislocation of 7.8 km, worse by 1.5 km. All other events are improved with a median mislocation of 10.8 km, reduced by 2.4 km.

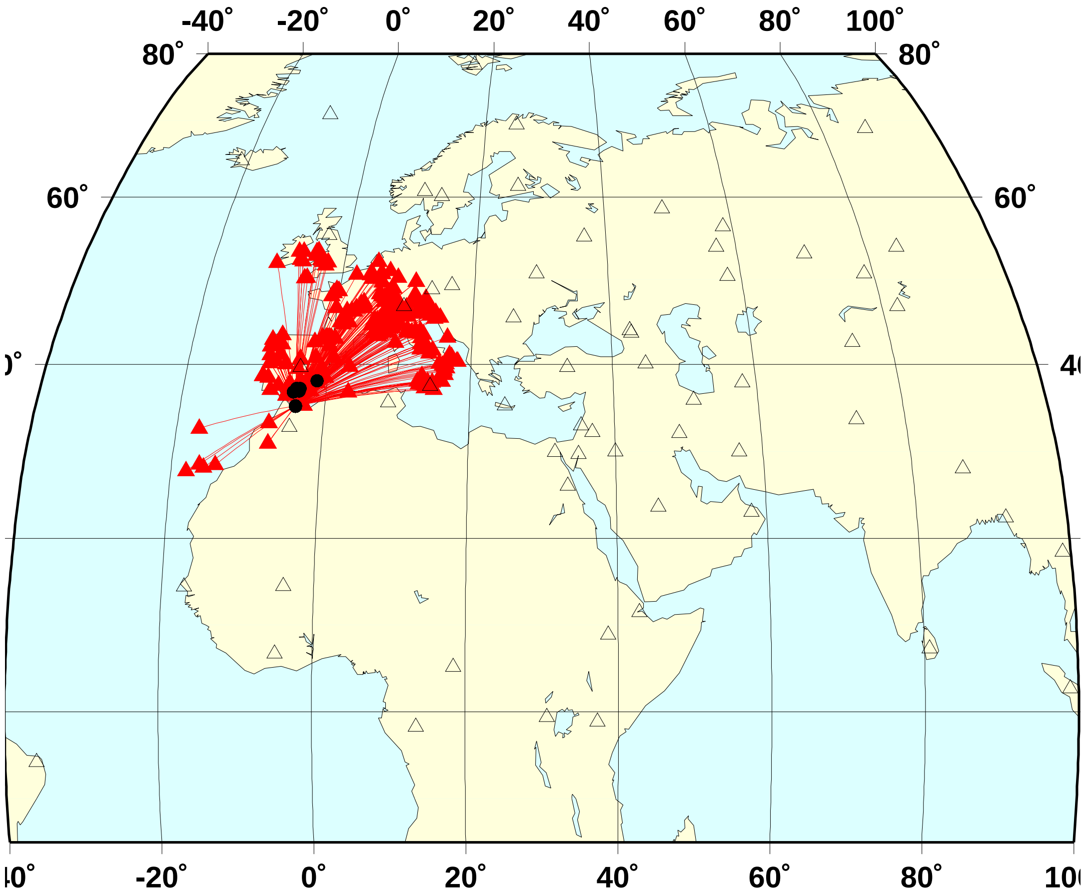


Figure 29a. The Morocco HDC cluster, Spain JHD cluster, and Spanish events in the Group-2 GT0-GT10 data set relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). These are GT5 events from the HDC/JHD analyses (Morocco/Spain clusters) and from the IGN. Station-event paths for defining Pn and Sn phases are plotted. Stations are shown as solid triangles and events are shown as solid circles. IMS stations are also plotted on the map (open triangles).

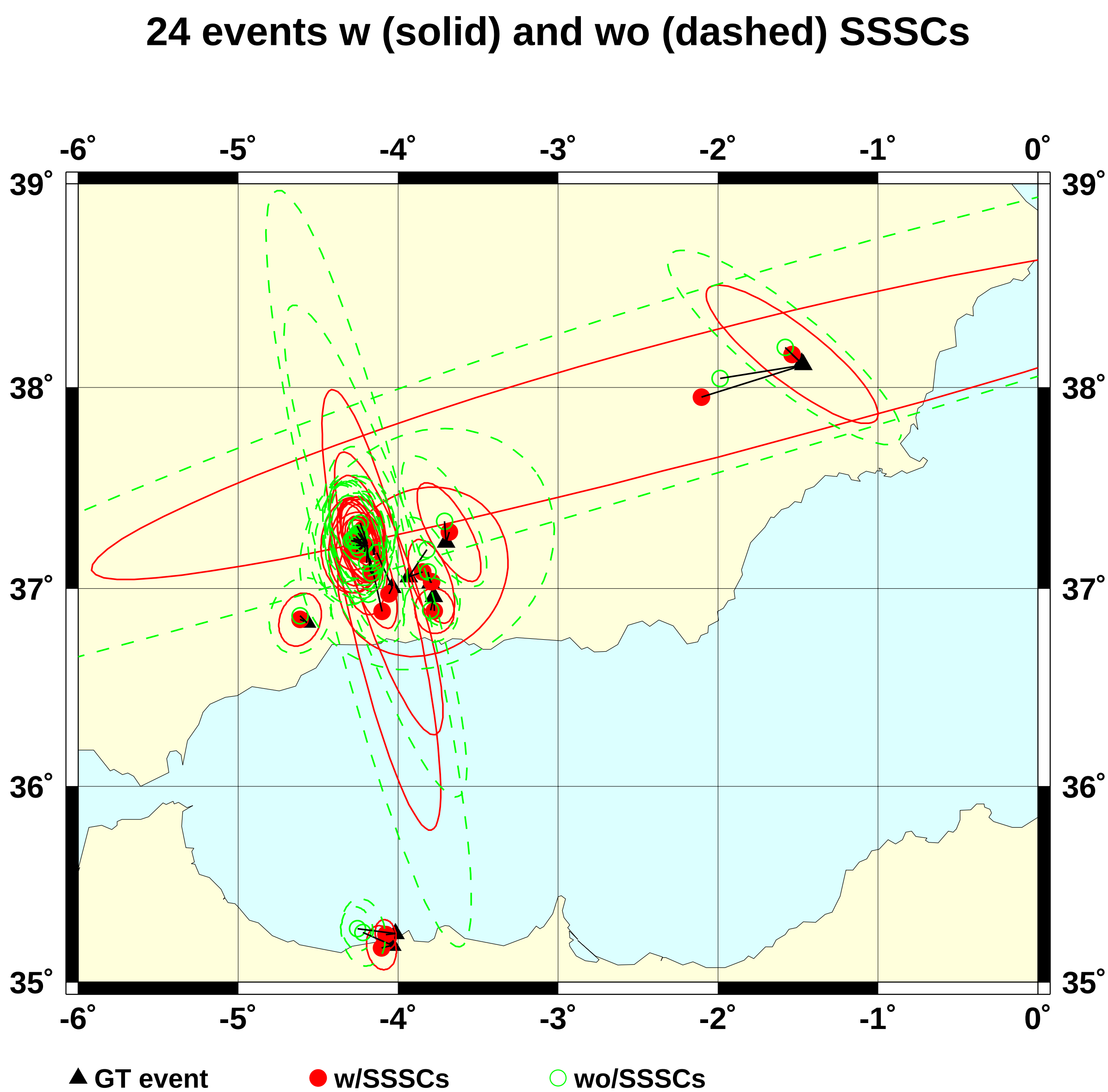


Figure 29b. Locations of the Morocco HDC cluster, Spanish JHD cluster, and Spanish events in the Group-2 GT0-GT10 data set when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). Event locations, error ellipses with (solid) and without (open/dashed) SSSCs, and GT locations for the 24 GT5 events are all plotted. Using SSSCs 16 events are improved with a median mislocation of 5.7 km, reduced by 4.7 km. In particular, 8 events are located within the GT5 bound (4 JHD and 4 IGN events). The two Morocco events are well located, within 6 km from GT and reduced by 12-16 km. With SSSCs 8 events are slightly deteriorated (median <1 km), with a median mislocation of 6.3 km. Three of the 10 JHD events are slightly deteriorated (<1 km), and 4 of the 12 IGN events are deteriorated, two of which are worse by 12-22 km.

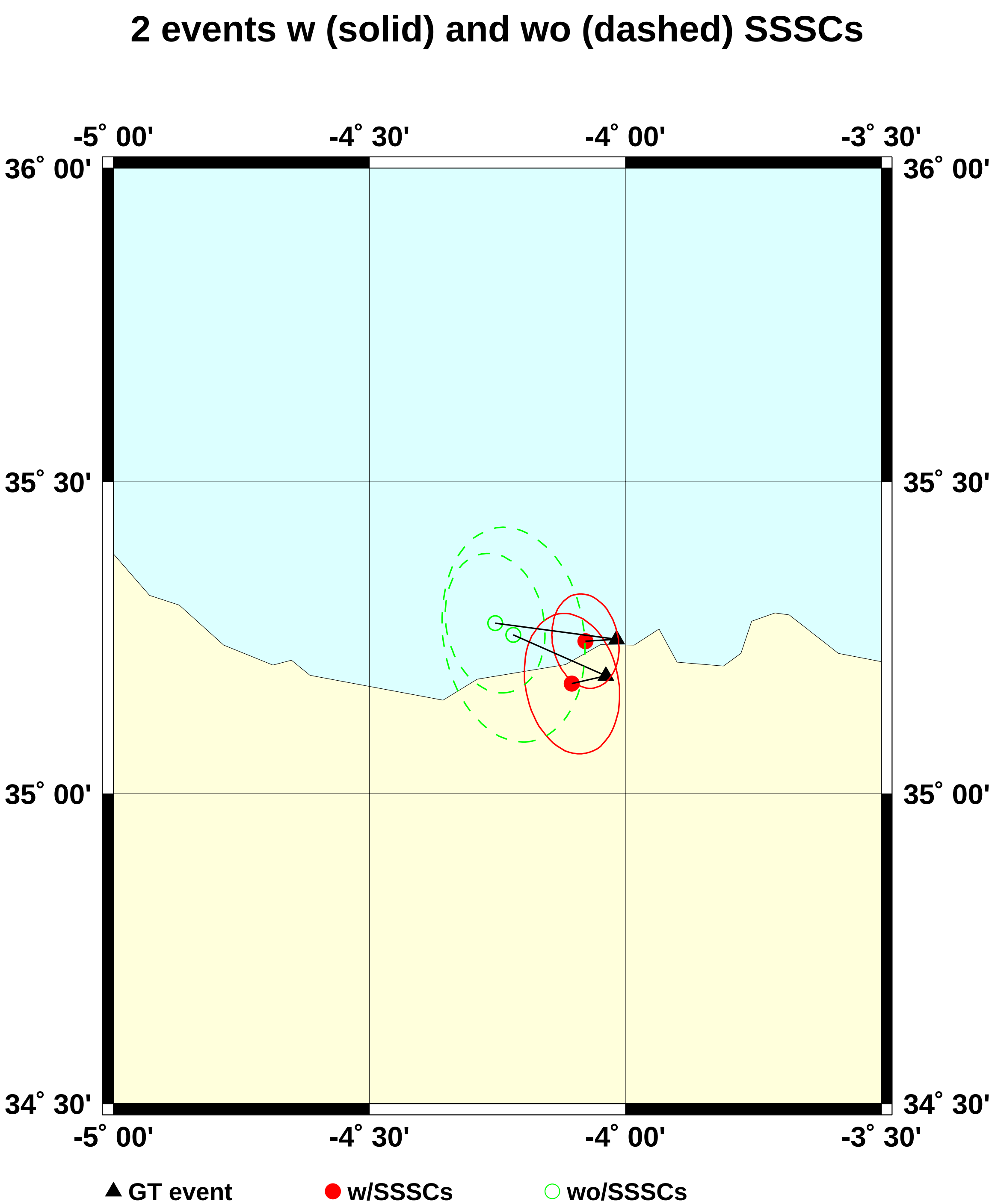


Figure 29c. Locations of the Morocco HDC cluster in the Group-2 GT0-GT10 data set when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). Event locations, error ellipses with (solid) and without (open/dashed) SSSCs, and GT locations for the two GT5 events are all plotted. Using SSSCs the mislocations are 5.6-6.2 km, improved by 11.8-16.2 km.

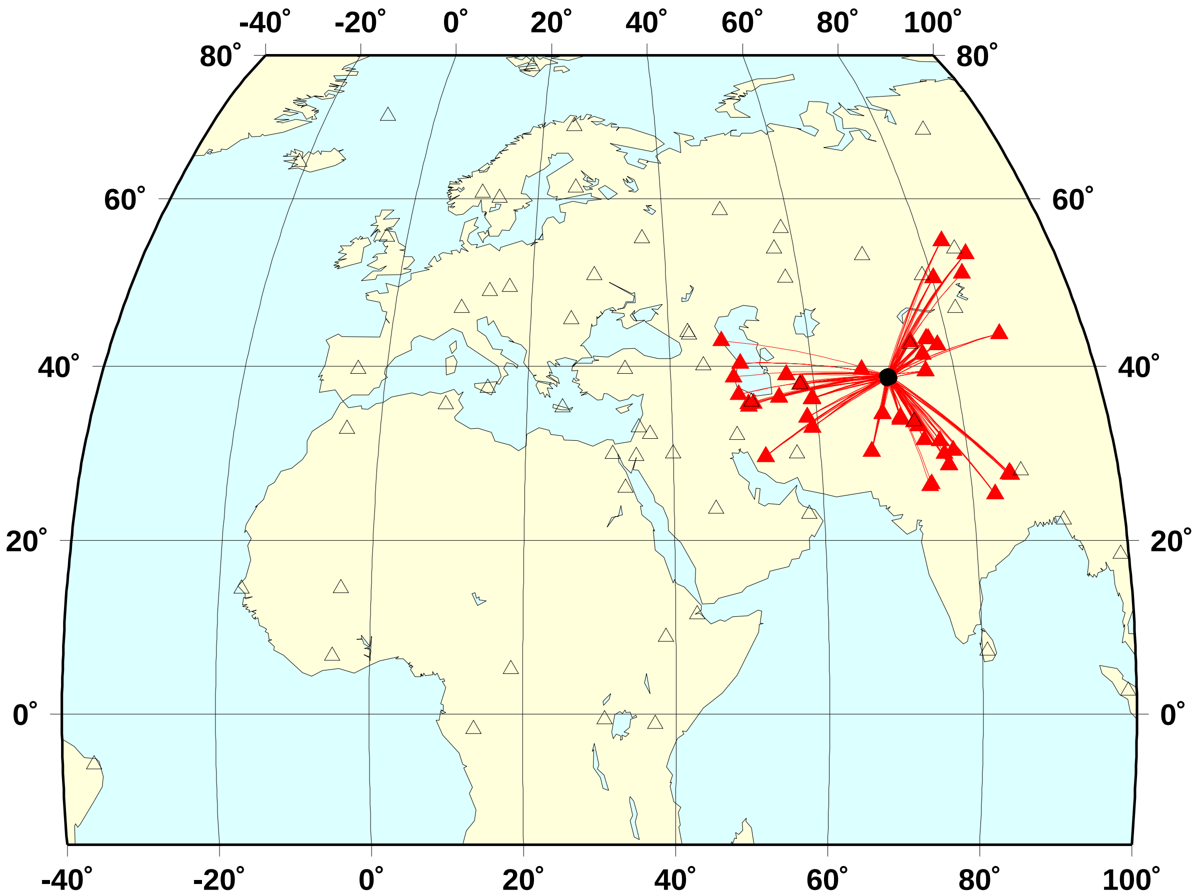


Figure 30a. The Garm cluster in the Group-2 GT0-GT10 data set relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). These are GT5 cluster events from the HDC analysis and only Pn phases are present. Station-event paths for defining Pn phases. Stations are shown as solid triangles and events are shown as solid circles. IMS stations are also plotted on the map (open triangles).

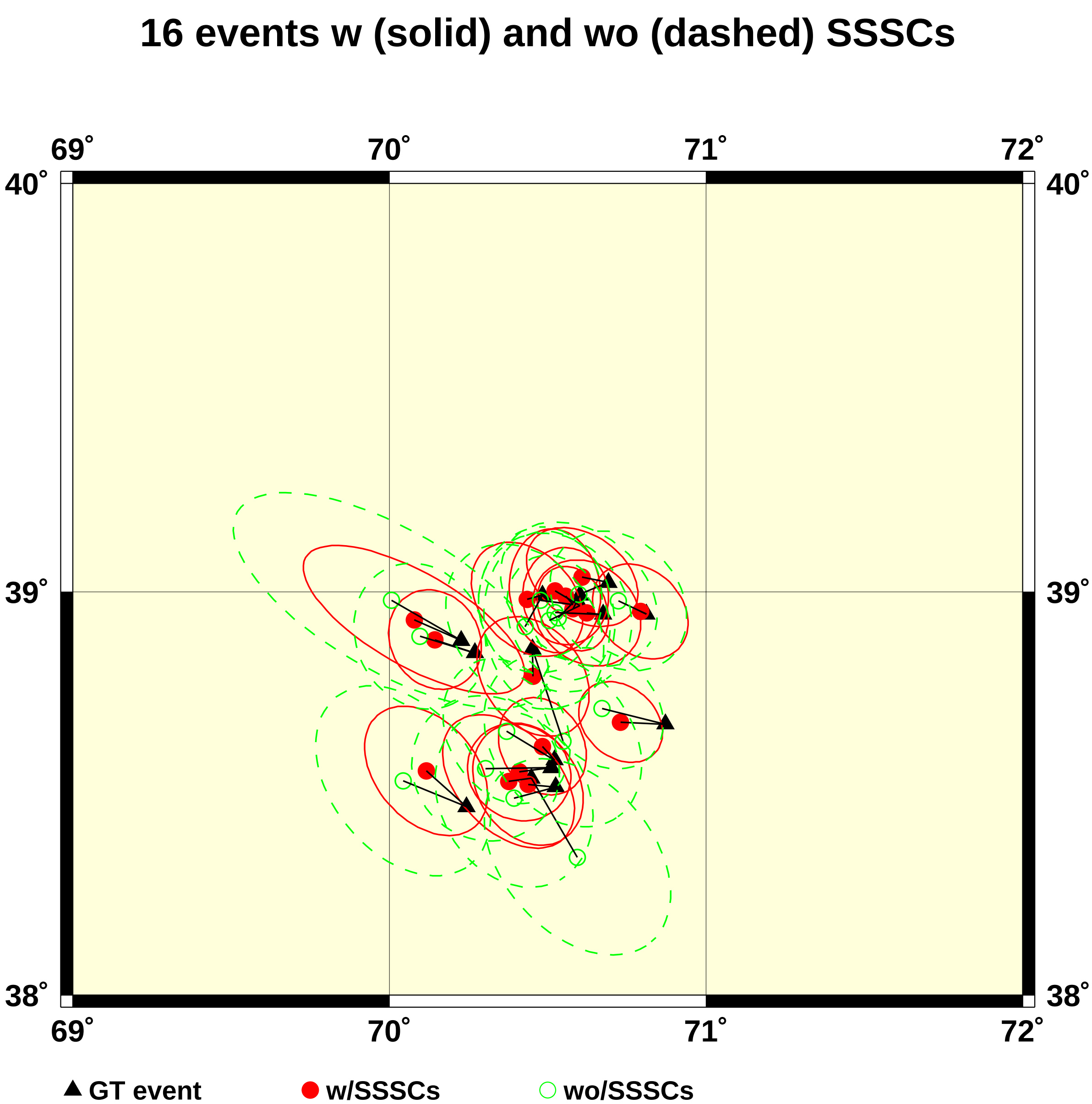


Figure 30b. Locations of the Garm cluster in the Group-2 GT0-GT10 data set when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). Event locations, error ellipses with (solid) and without (open/dashed) SSSCs. GT locations are also plotted. Using SSSCs all events are improved with a median mislocation of 7.5 km, reduced by 5.9 km. In particular, 6 out of 16 events are located within 5 km.

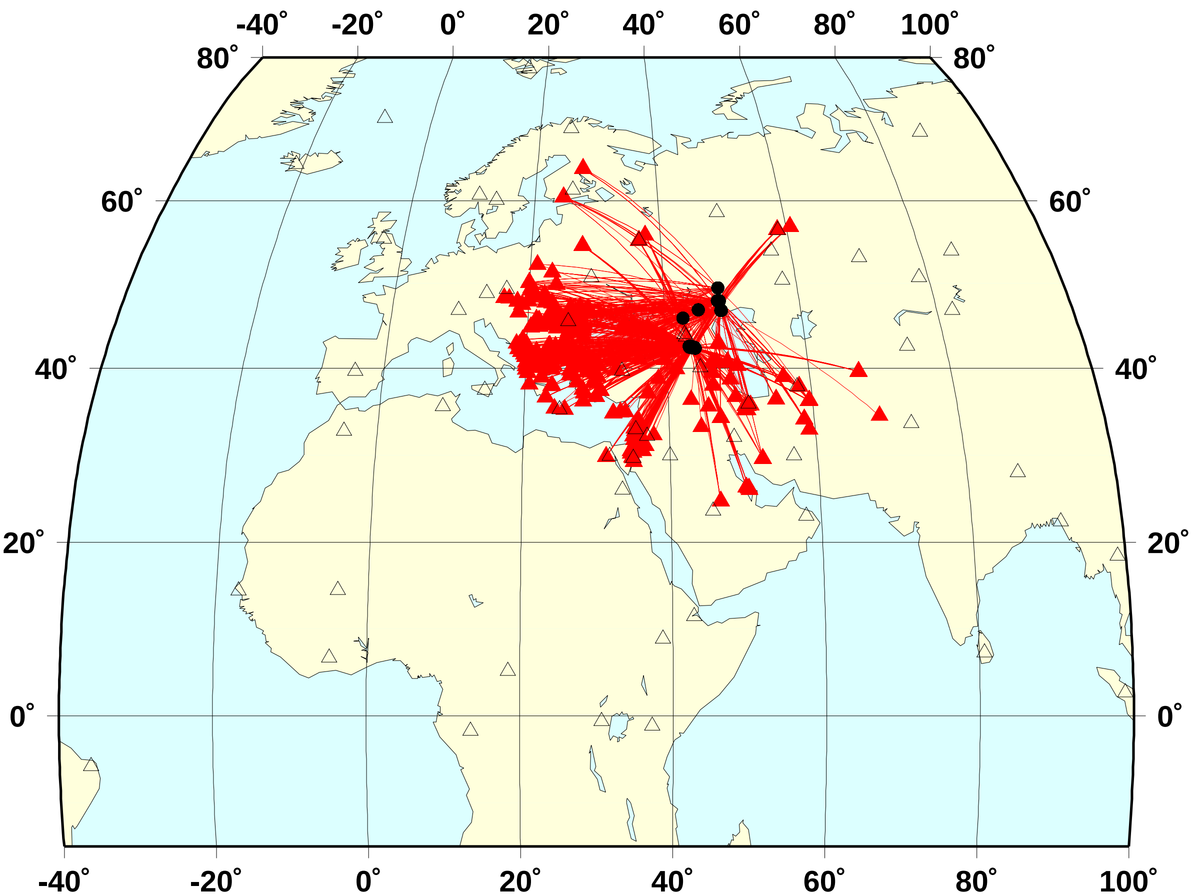


Figure 31a. The PNEs and the Azgir and Racha clusters in the Group-2 GT0-GT10 data set relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). The cluster events are GT5 from the HDC analysis and only Pn phases are present. The PNEs are GT1 with arrivals from the EHB catalog. Station-event paths for defining Pn and Sn phase are plotted. Stations are shown as solid triangles and events are shown as solid circles. IMS stations are also plotted on the map (open triangles).

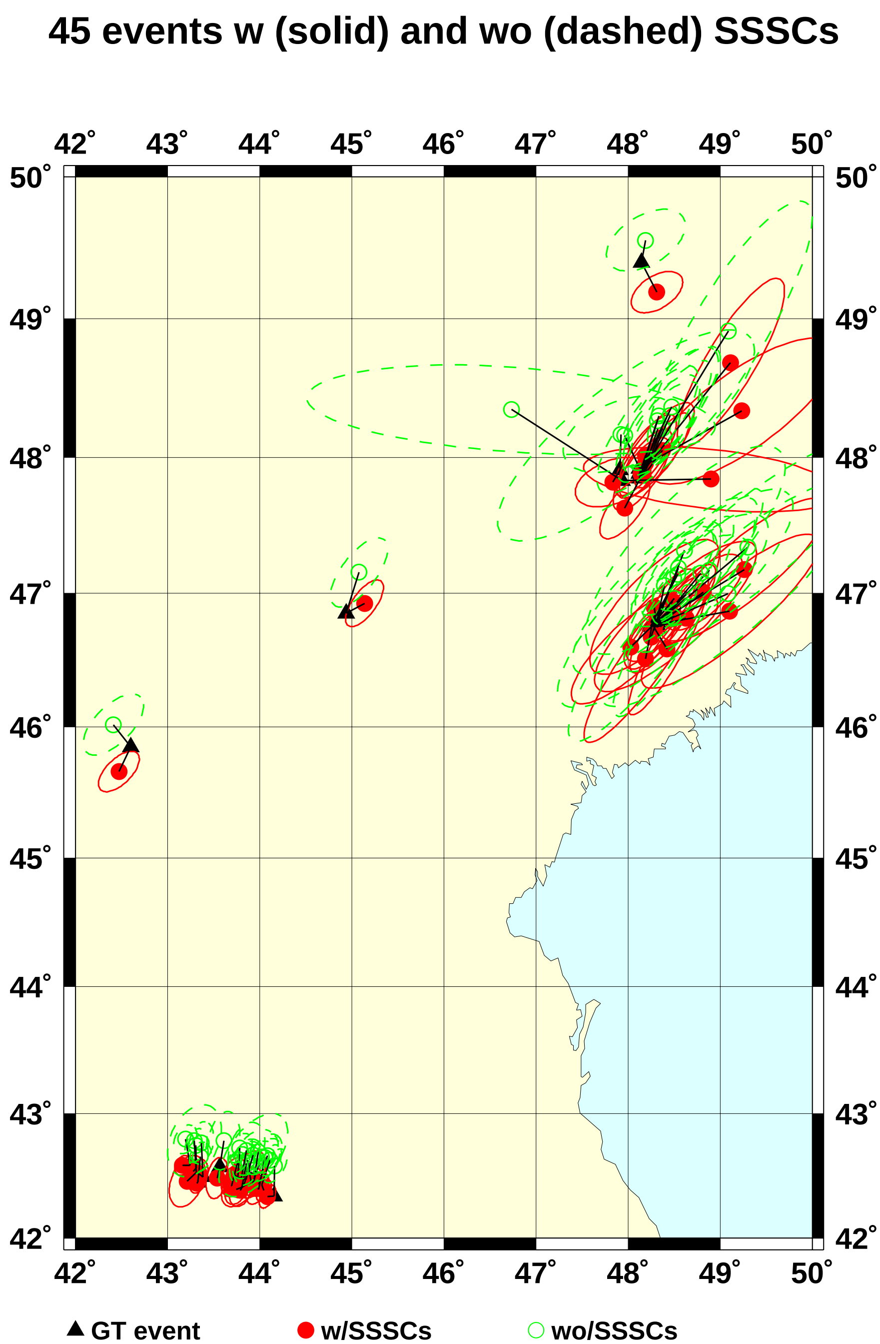


Figure 31b. Locations of the PNEs and the Azgir and Racha clusters in the Group-2 GT0-GT10 data set when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). Event locations, error ellipses with (solid) and without (open/dashed) SSSCs, and GT locations for the 52 events are all plotted. With SSSCs 40 events are improved, with a median mislocation of 10.5 km, reduced by 20.7 km. Five events are deteriorated with a median deterioration of 27 km, worse by 8.8 km. With SSSCs 10 events are located within the GT5 bound.

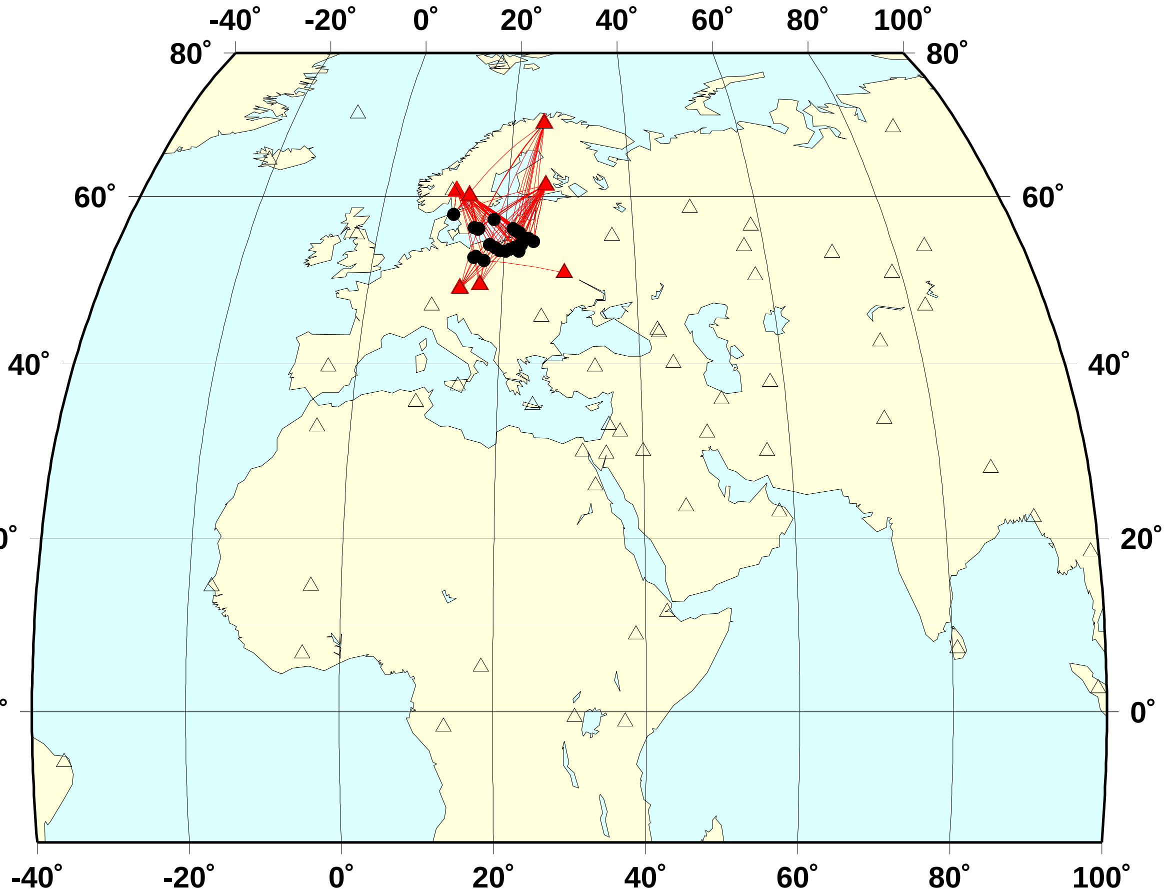


Figure 32a. The Polonaise and Eurobridge experiments in the Group-2 GT0-GT10 data set relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). They are GT0-GT2 events with arrivals from the IMS and other stations. Station-event paths for defining Pn and Sn phase are plotted. Stations are shown as solid triangles and events are shown as solid circles. IMS stations are also plotted on the map (open triangles).

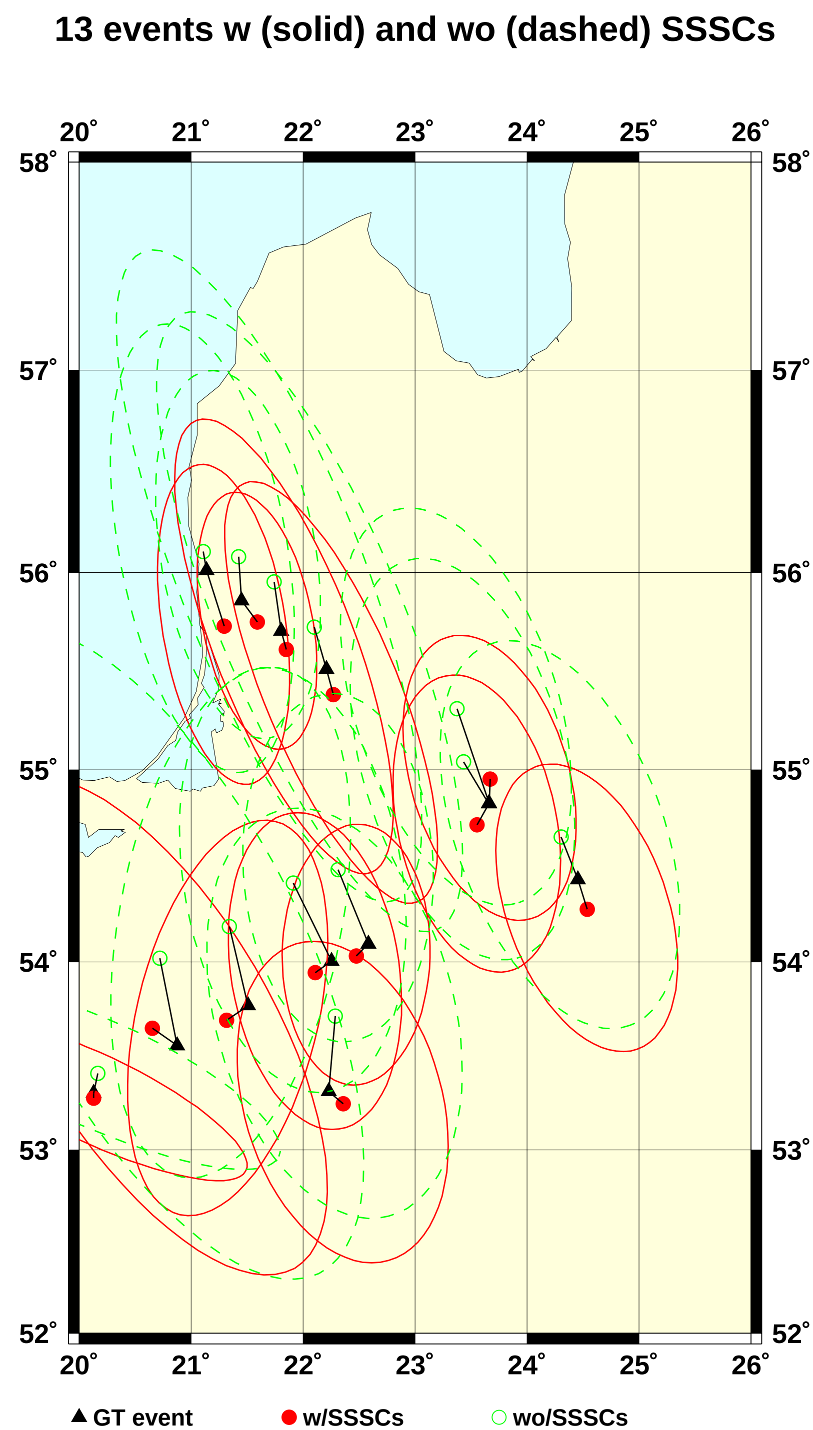


Figure 32b. Locations of the Polonaise and Eurobridge experiments in the Group-2 GT0-GT10 data set when relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). Event locations, error ellipses with (solid) and without (open/dashed) SSSCs, and GT locations for the 14 GT0-GT2 events are all plotted. With SSSCs 13 events are improved with a median mislocation of 14 km, reduced by 24.7 km. One event has deteriorated mislocation of 32.6 km, worse by 21.8 km.

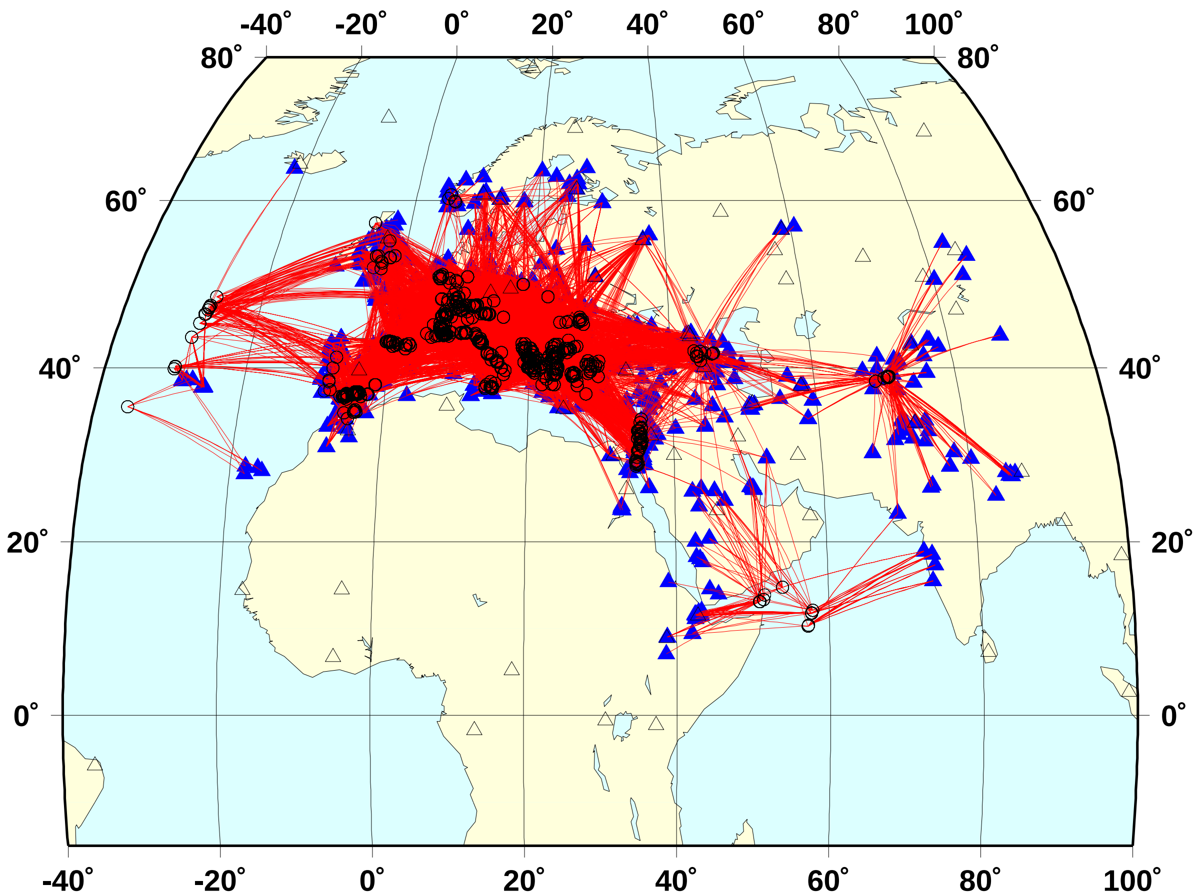


Figure 33a. MORT and estimated GT5 EHB events regional Pn paths (Sections 5.2-5.3).

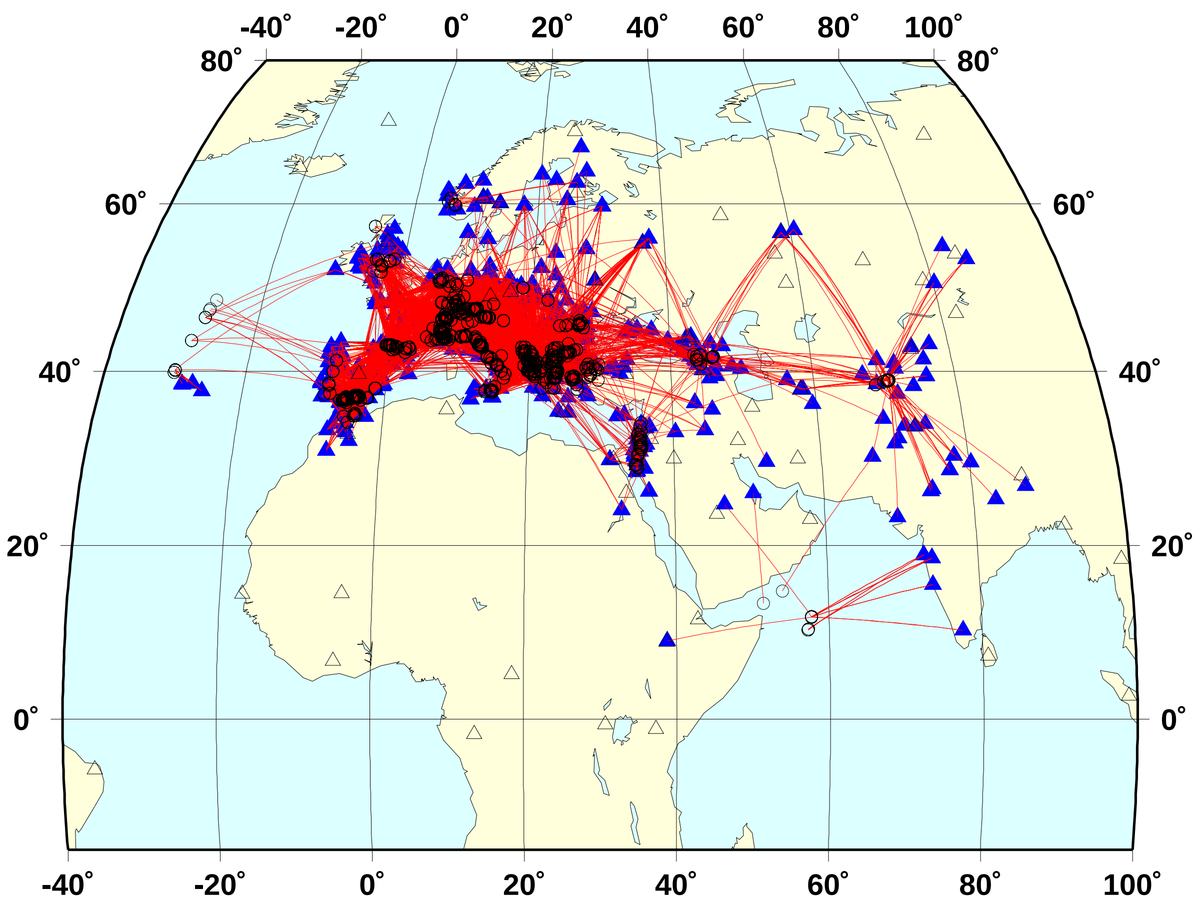


Figure 33b. MORT and estimated GT5 EHB events regional Sn paths (Sections 5.2-5.3).

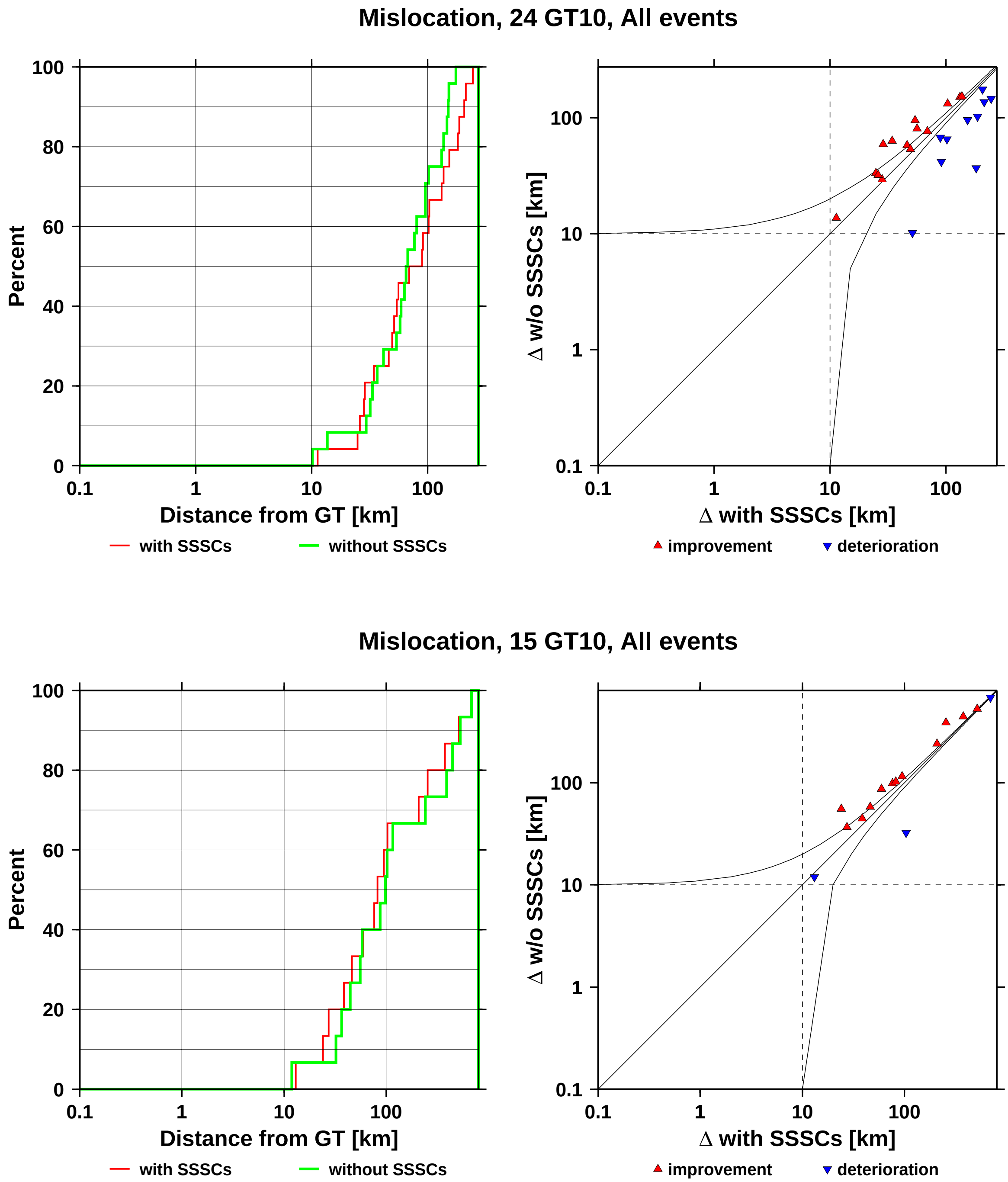


Figure 34. Mislocations of the MORT GT10 events using Pn and Sn phases from all stations, with and without SSSCs (Section 5.2). (a) Using all Pn and Sn phases. (b) Using Pn and Sn phases within 15 degrees. (Left) Cumulative plot of mislocation. (Right) Comparisons of mislocation with (red triangle) and without (blue inverse triangle) SSSCs. The10-km bound (dashed lines) and GT10 uncertainty (curved lines) are plotted. Symbols above the diagonal line indicate improvement with SSSCs.

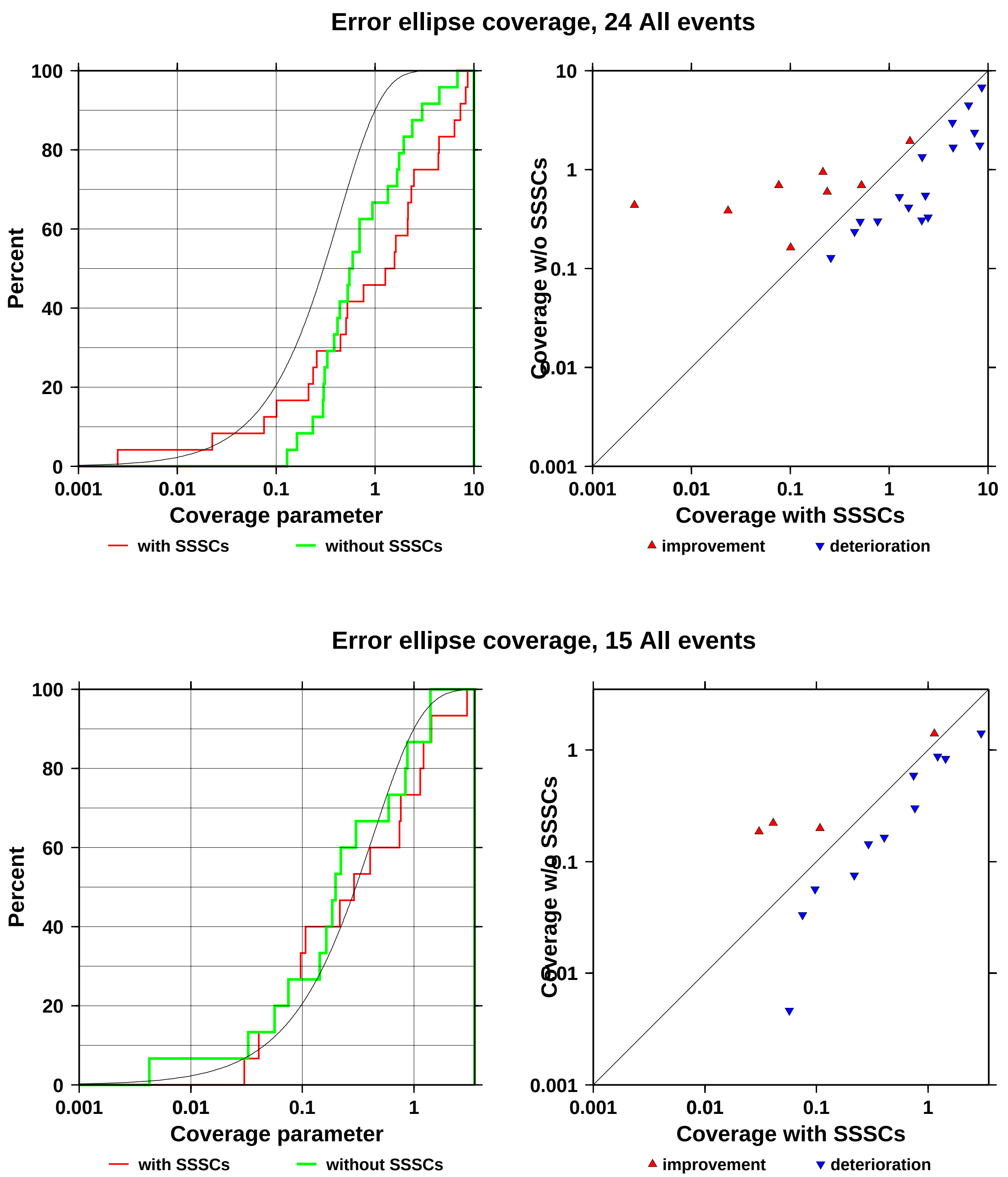


Figure 35. Ellipse coverages of the MORT GT10 events using Pn and Sn phases from all stations, with and without SSSCs (Section 5.2). (a) Using all Pn and Sn phases. (b) Using Pn and Sn phases within 15 degrees. (Left) Cumulative plot of error ellipse coverage. The χ^2distribution is also plotted. (Right) Comparisons of ellipse coverage with (red triangle) and without (blue inverse triangle) SSSCs. Symbols above the diagonal line indicate improvement with SSSCs.

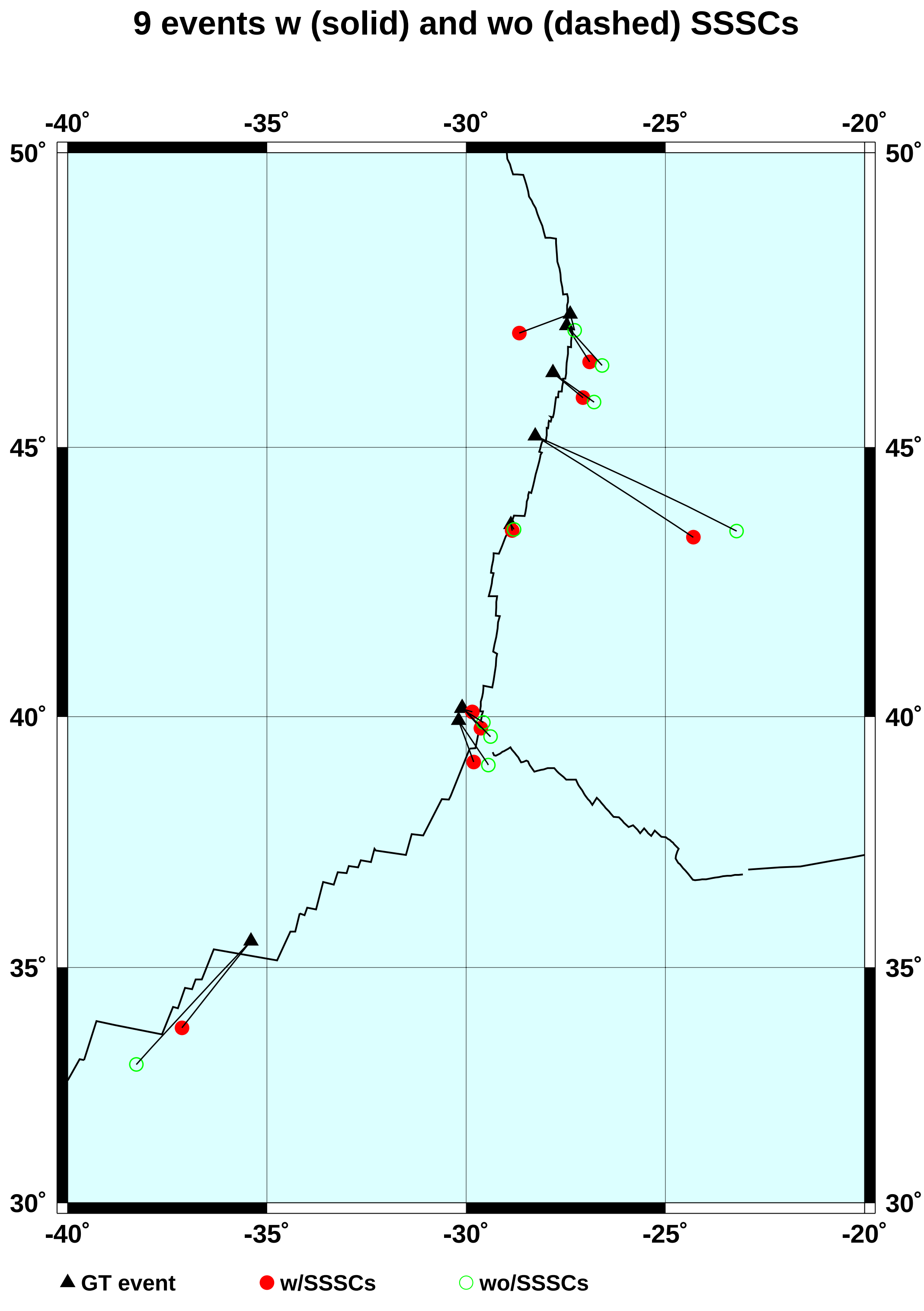


Figure 36. Location of the MORT GT10 events in North Atlantic when relocated using Pn and Sn phases from all stations within 15 degrees, with and without SSSCs (Section 5). Event locations, error ellipses with (solid) and without (open/dashed) SSSCs, and GT locations for the 13 GT10 events are all plotted.

6 events w (solid) and wo (dashed) SSSCs

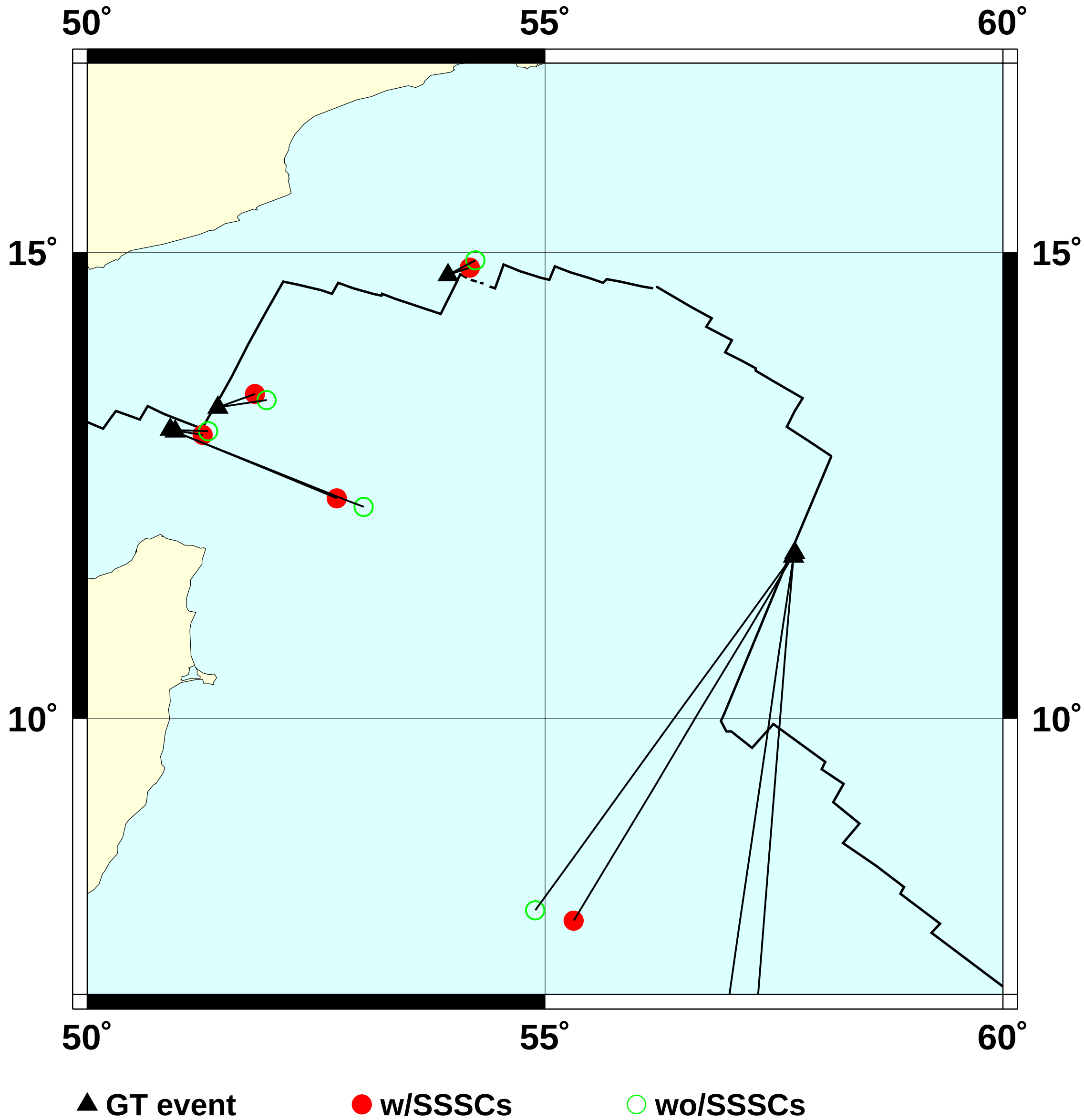


Figure 37. Location of the MORT GT10 events in the Gulf of Aden when relocated using Pn and Sn phases from all stations within 15 degrees, with and without SSSCs (Section 5). Event locations, error ellipses with (solid) and without (open/dashed) SSSCs, and GT locations for the 11 GT10 events are all plotted.

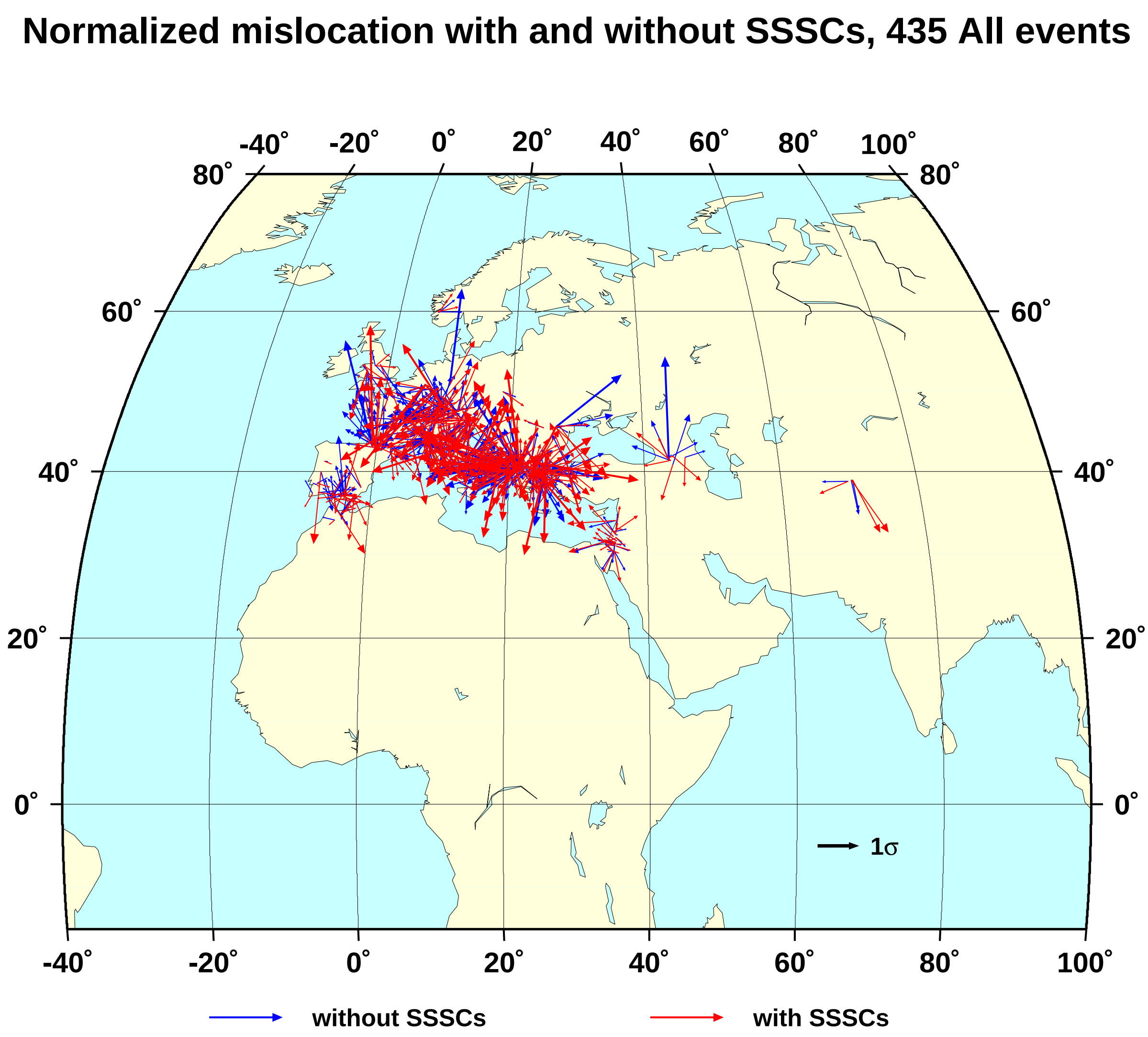


Figure 38. Normalized mislocations with (red) and without (blue) SSSCs when the estimated GT5 EHB events are relocated using Pn and Sn phases from all stations, with and without SSSCs (Section 5.1). The direction of the arrows are from the GT to the relocation. The baseline scale is 1, i.e. 90% coverage is met.

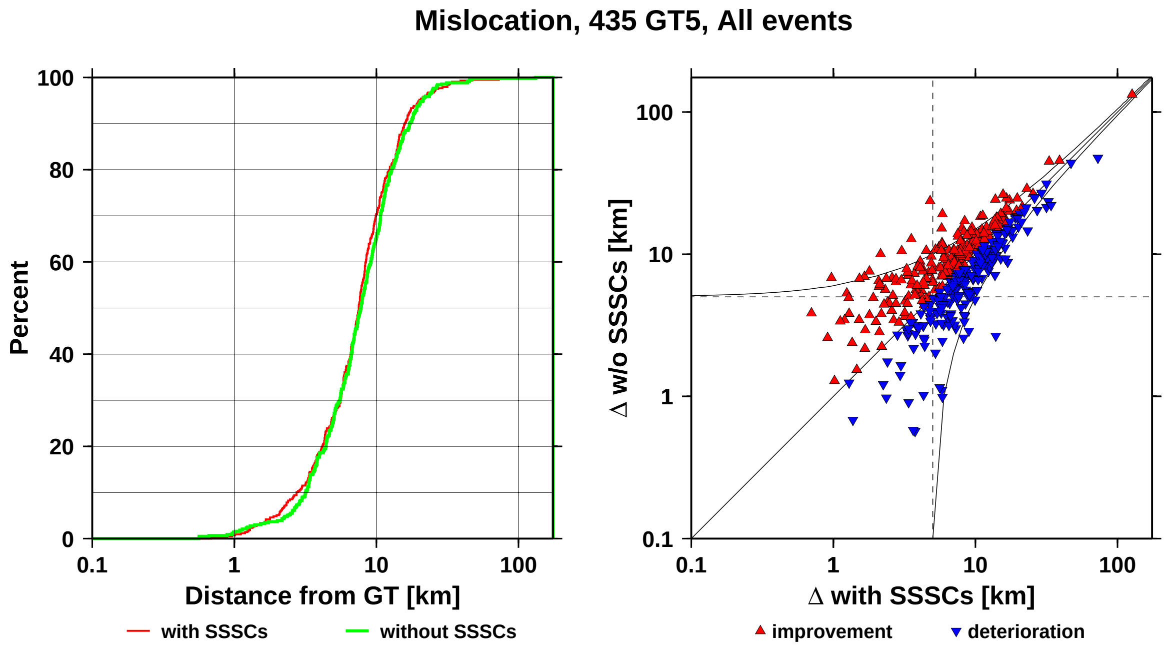


Figure 39. Mislocations of the estimated EHB GT5 events with and without SSSCs (Section 5.3). (Left) Cumulative plot of mislocation. (Right) Comparisons of mislocation with (red triangle) and without (blue inverse triangle) SSSCs. The 5-km bound (dashed lines) and GT5 uncertainty (curved lines) are plotted. Symbols above the diagonal line indicate improvement with SSSCs.

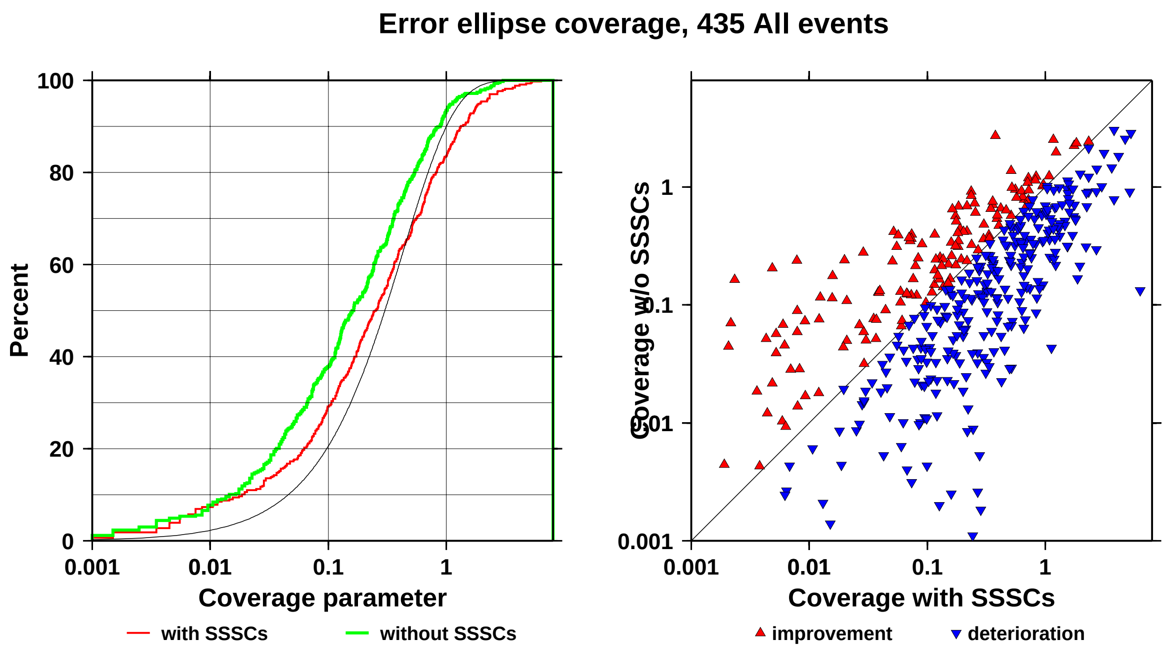


Figure 40. Ellipse coverages of the estimated EHB GT5 events with and without SSSCs (Section 5.3). (Left) Cumulative plot of error ellipse coverage. The χ^2distribution is also plotted. (Right) Comparisons of ellipse coverage with (red triangle) and without (blue inverse triangle) SSSCs. Symbols above the diagonal line indicate improvement with SSSCs.

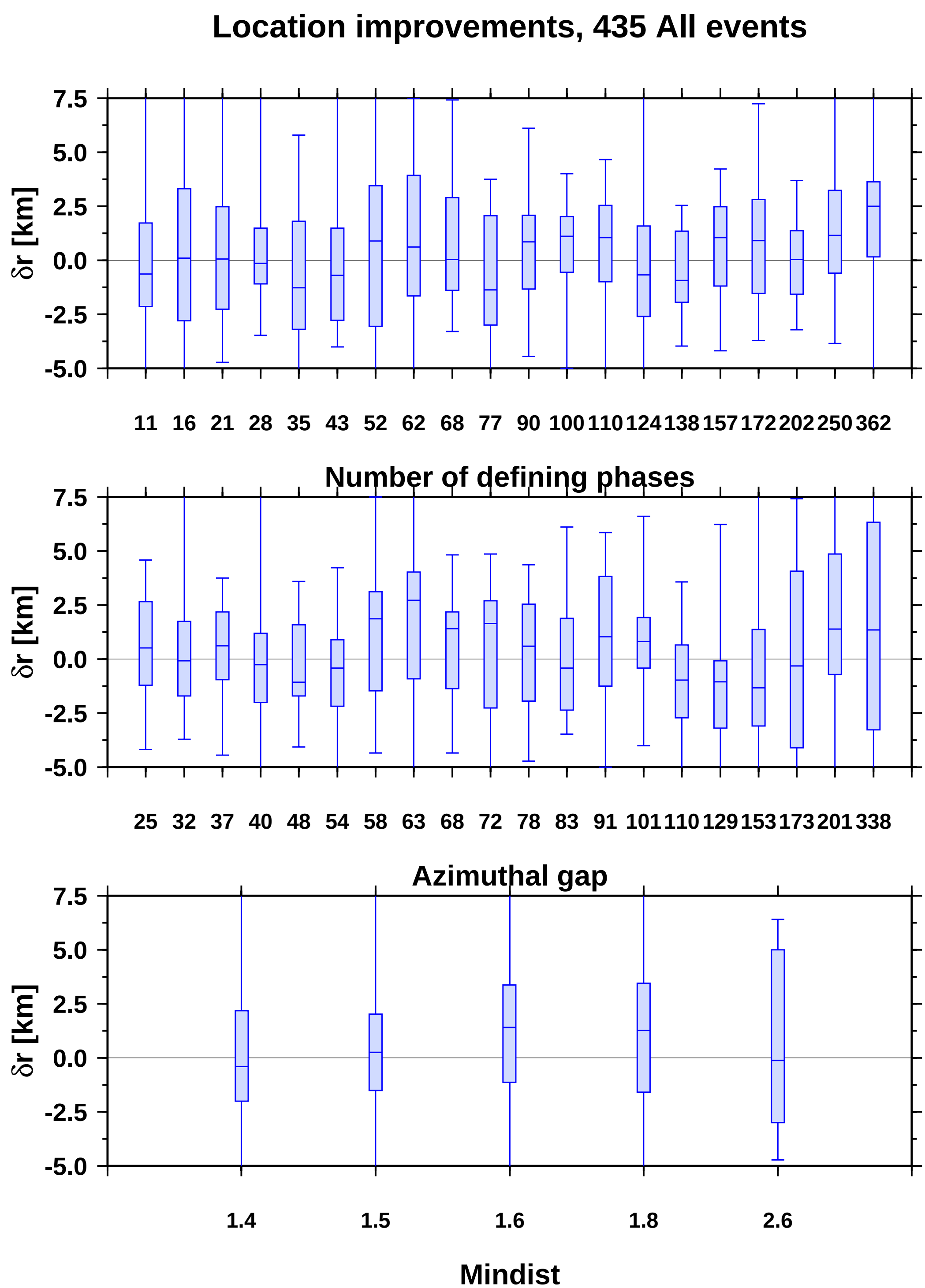


Figure 41. Location improvements of the estimated EHB GT5 events with SSSCs versus ndef, azimuthal gap, and error ellipse axis ratio (Section 5.3). In each plot the bins vary according to the cumulative distributions, and only data within the 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

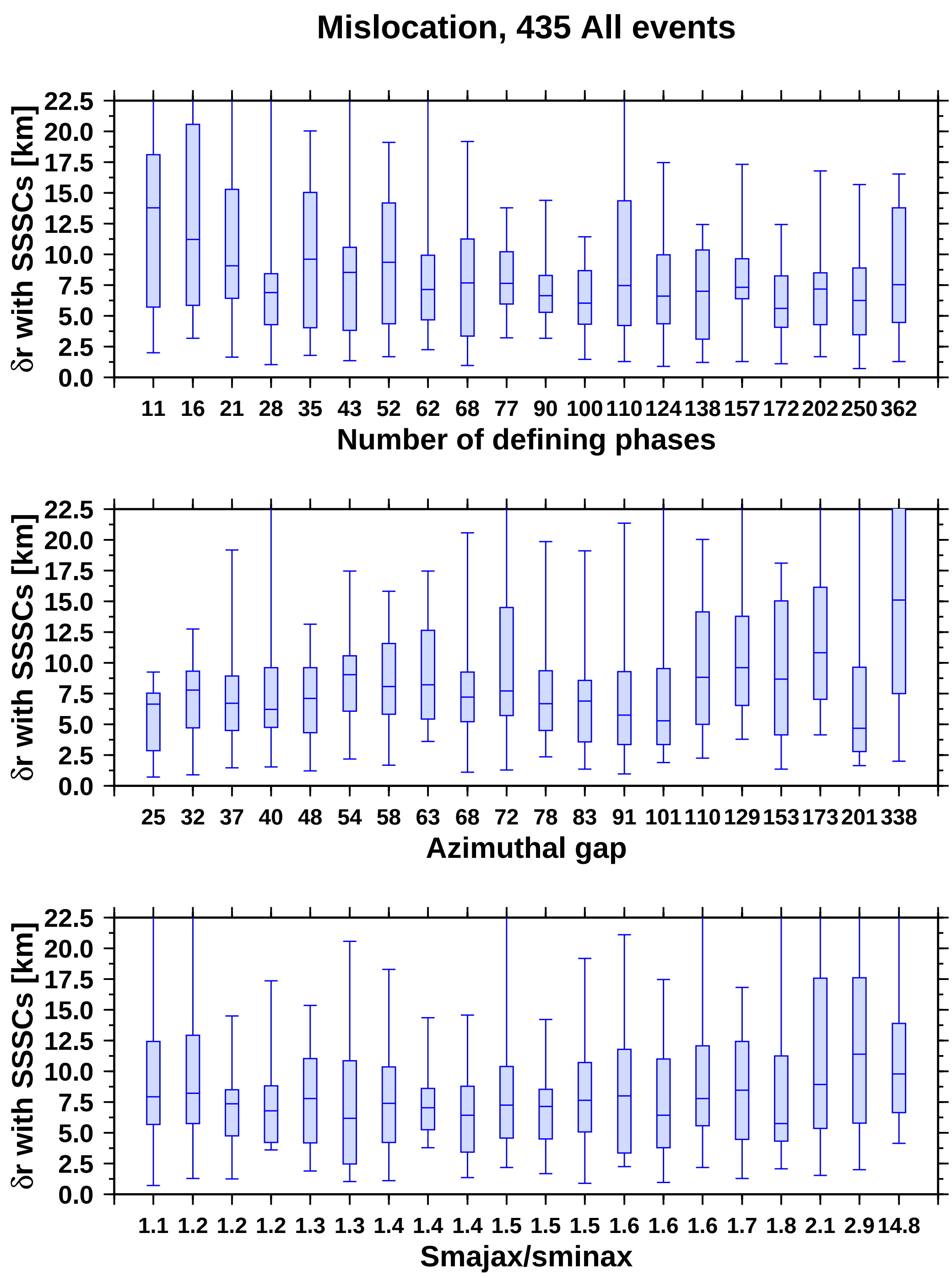


Figure 42. Mislocations of the estimated EHB GT5 events with SSSCs versus ndef, azimuthal gap, and error ellipse axis ratio (Section 5.3). In each plot the bins vary according to the cumulative distributions, and only data within 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

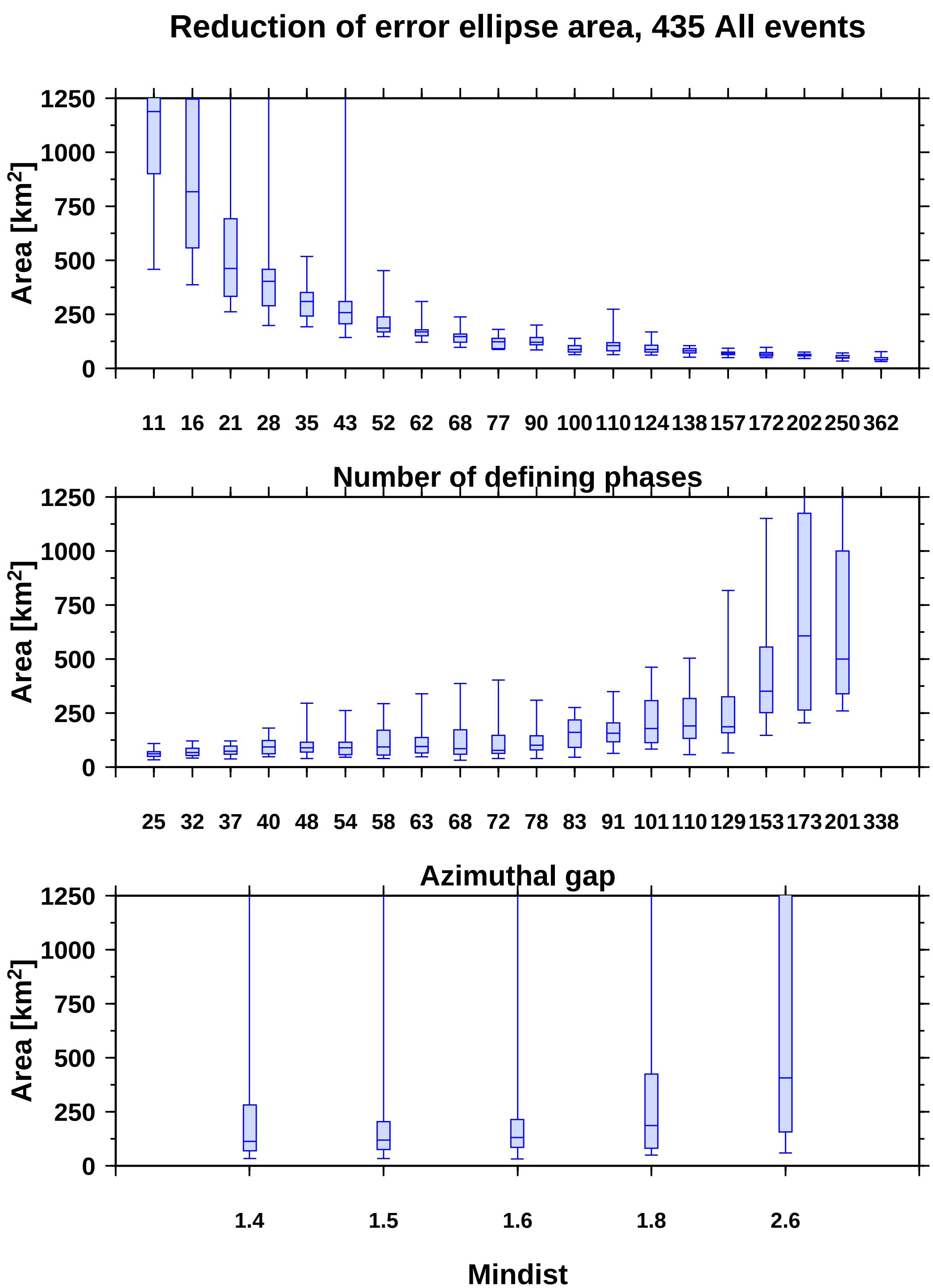


Figure 43. Improvement on error ellipse areas of the estimated EHB GT5 events with SSSCs versus ndef, azimuthal gap, and error ellipse axis ratio (Section 5.3). In each plot the bins vary according to the cumulative distributions, and only data within the 95th percentile are shown. The filled rectangle (with the median value inside) shows data in the 25-75% quantiles, and the bars show the range.

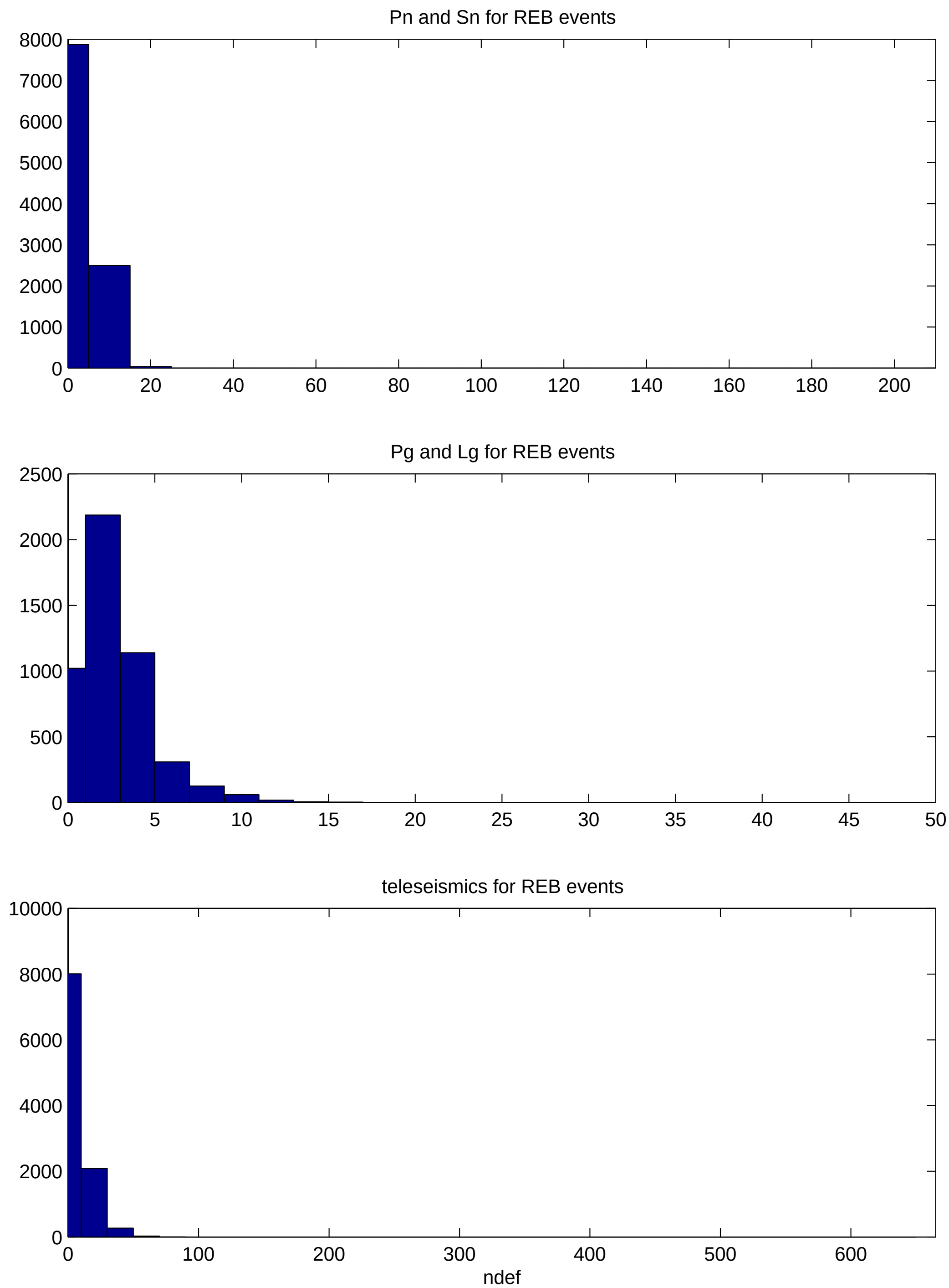


Figure 44a. Histograms of ndef by phase type for PIDC REB events during 1995/01/01-2000/12/31. (top) Pn and Sn phases. (middle) Pg and Lg phases. (bottom) teleseismic phases.

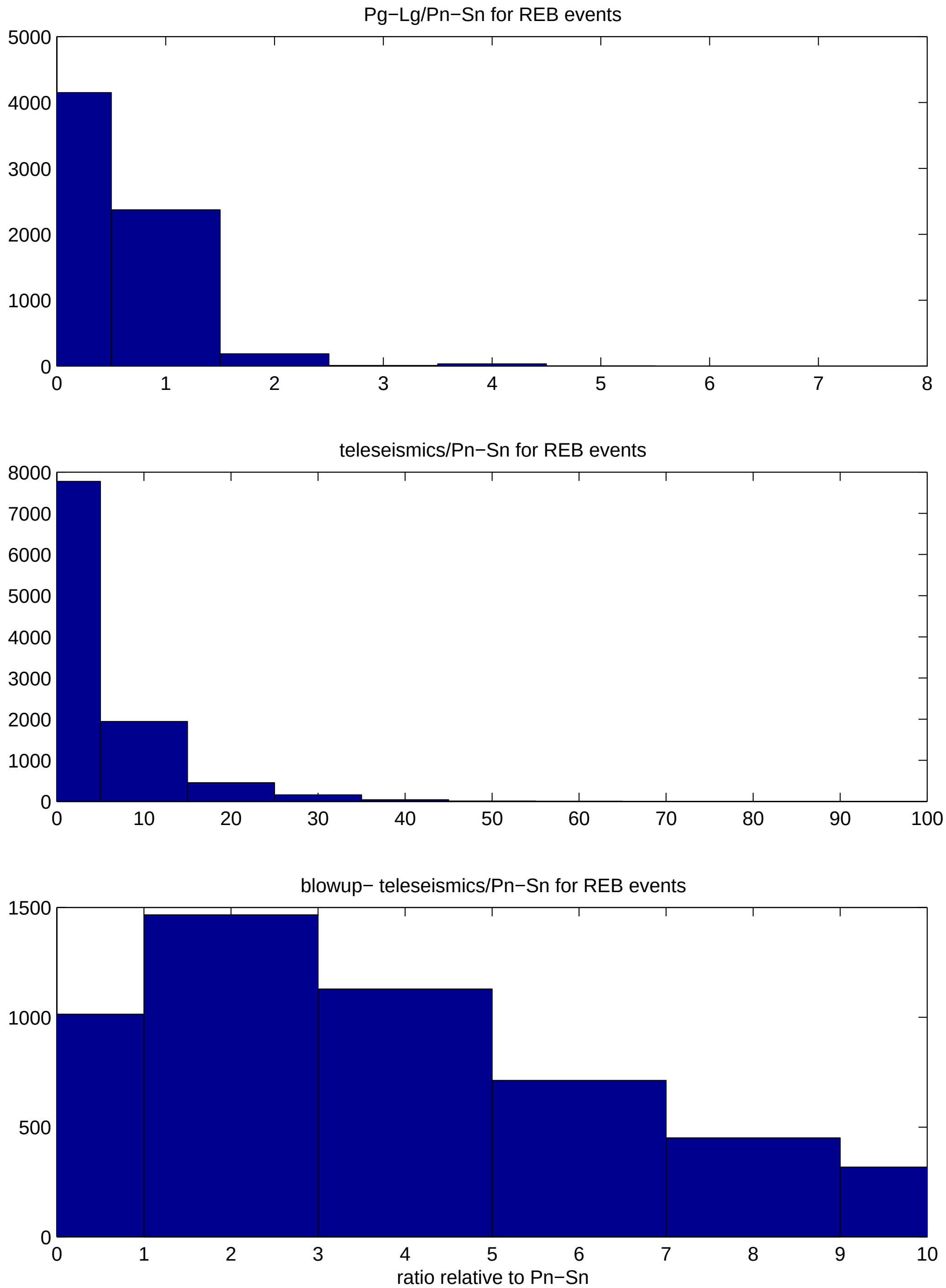


Figure 44b. Histograms of ndef ratio relative to Pn and Sn phases for PIDC REB events during 1995/01/01-2000/12/31. (top) Ratio of Pg and Lg phases relative to Pn and Sn phases. (middle) Ratio of teleseismic phases relative to Pn and Sn phases. (bottom) Blowup of the middle diagram.

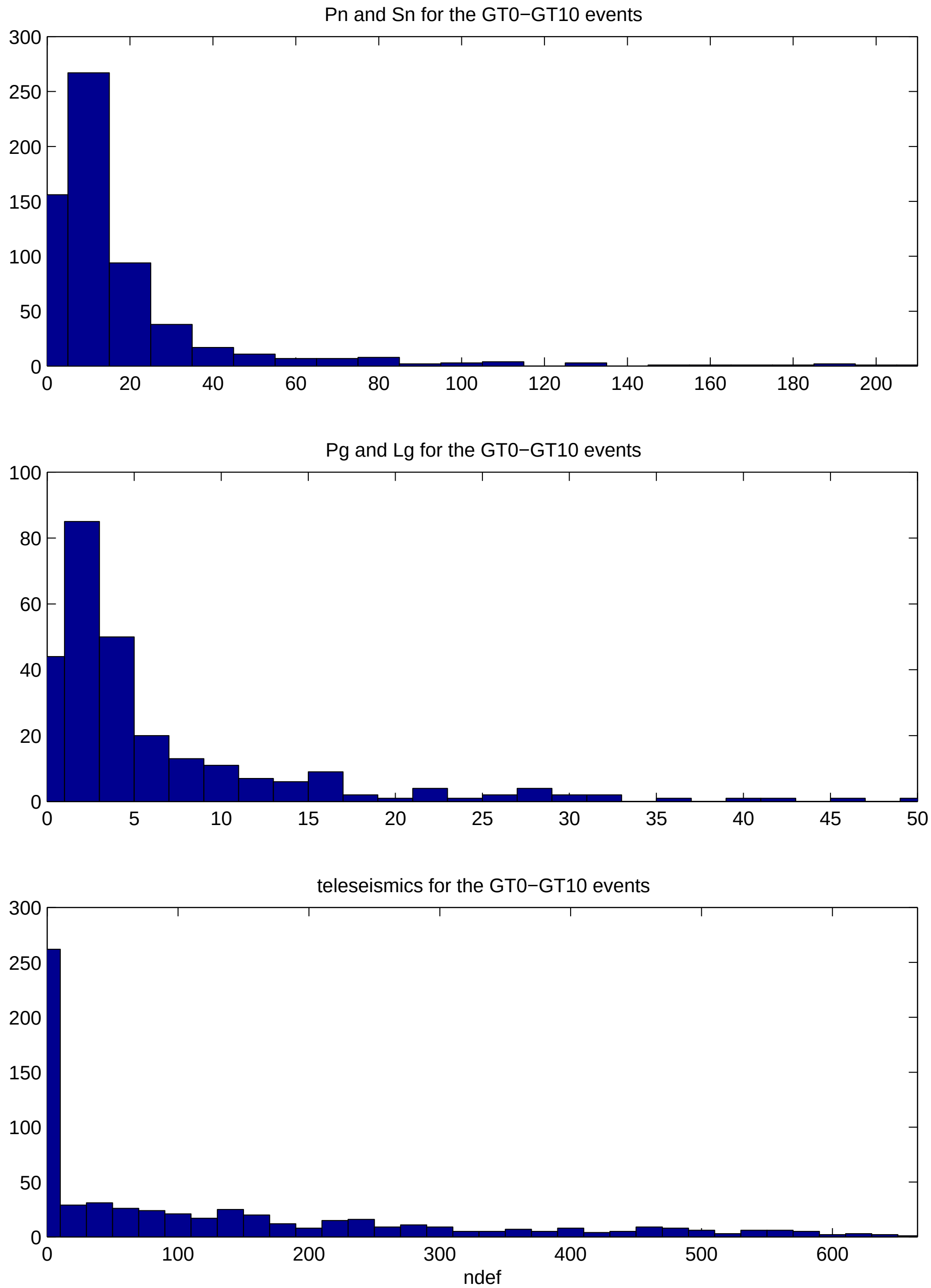


Figure 45a. Histograms of ndef by phase type for events in the Group-2 GT0-GT10 data set. (top) Pn and Sn phases. (middle) Pg and Lg phases. (bottom) teleseismic phases.

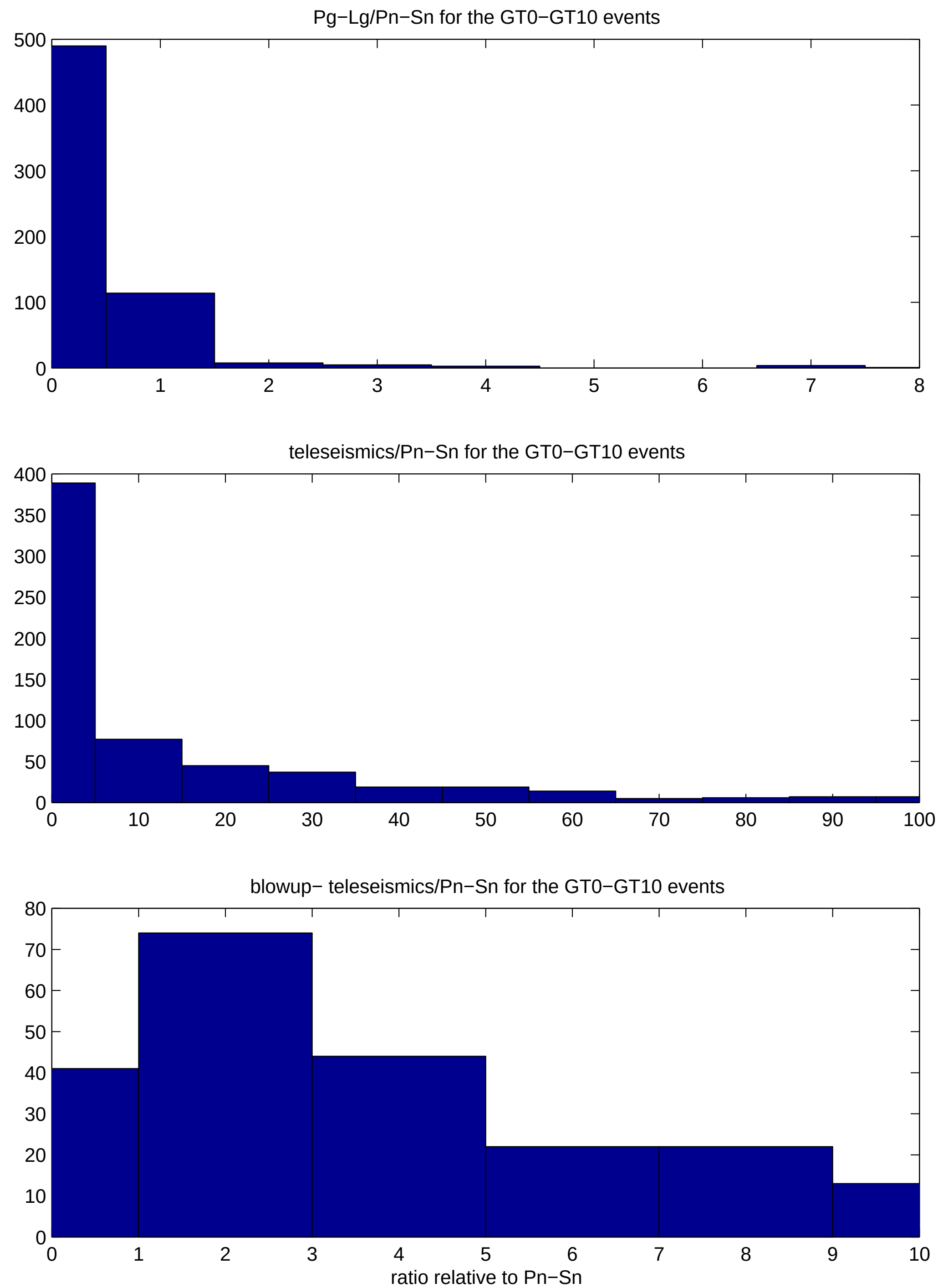


Figure 45b. Histograms of ndef ratio relative to Pn and Sn phases for events in the Group-2 GT0-GT10 data set. (top) Ratio of Pg and Lg phases relative to Pn and Sn phases. (middle) Ratio of teleseismic phases relative to Pn and Sn phases. (bottom) Blowup of the middle diagram.

Appendix 1. Evaluation metrics

1. DISTANCE FROM GT (n=):

total number of solutions: with and without SSSCs: sdev, average deviation, Student t-significance test, median distance with and without spread, percentiles, minimum, maximum, Wilcoxon signed rank test.

% (n=) solutions are closer to GT: with and without SSSCs: sdev, average deviation, Student t-significance test, median distance with and without spread, percentiles, minimum, maximum, Wilcoxon signed rank test.

% (n=) solutions moved away from GT: with and without SSSCs: sdev, average deviation, Student t-significance test, median distance with and without spread, percentiles, minimum, maximum, Wilcoxon signed rank test.

% (n=) solutions are closer to GT by 20%: with and without SSSCs: sdev, average deviation, Student t-significance test, median distance with and without spread, percentiles, minimum, maximum, Wilcoxon signed rank test.

% (n=) solutions moved away from GT by 20%: with and without SSSCs: sdev, average deviation, Student t-significance test, median distance with and without spread, percentiles, minimum, maximum, Wilcoxon signed rank test.

2. DISTANCE FROM GT as a function of ndef:

Same metrics as in 1.

3. AREA OF ERROR ELLIPSES (n=):

total number of solutions: with and without SSSCs: sdev, average deviation, Student t-significance test, median distance with and without spread, percentiles, minimum, maximum, Wilcoxon signed rank test.

% (n=) ellipses are smaller: with and without SSSCs: sdev, average deviation, Student t-significance test, median distance with and without spread, percentiles, minimum, maximum, Wilcoxon signed rank test.

% (n=) ellipses are larger: with and without SSSCs: sdev, average deviation, Student t-significance test, median distance with and without spread, percentiles, minimum, maximum, Wilcoxon signed rank test.

% (n=) ellipses are smaller by 20%: with and without SSSCs: sdev, average deviation, Student t-significance test, median distance with and without spread, percentiles, minimum, maximum, Wilcoxon signed rank test.

% (n=) ellipses are larger by 20%: with and without SSSCs: sdev, average deviation, Student t-significance test, median distance with and without spread, percentiles, minimum, maximum, Wilcoxon signed rank test.

4. ELLIPSE COVERAGE

90% ERROR ELLIPSE COVERAGE W/O SSSCs

90% ERROR ELLIPSE COVERAGE WITH SSSCs

5. TRINITY

events with less than 1000 sqkm error ellipse with GT

inside the ellipse and within 18 km distance from GT

w/o SSSCs

with SSSCs

6. ORIGIN TIME DIFFERENCE FROM GT (n=):

Same metrics as in 1.

7. ORIGIN TIME ERROR (n=):

Same metrics as in 1.

8. STANDARD DEVIATION OF OBSERVATIONS (n=):

Same metrics as in 1.